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HIGH EFFICIENCY ACTIVE MATRIX
LIQUID CRYSTAL DISPLAYS (HEAMLCD)

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BAE SYSTEMS MEMS OPTICAL

NOVEMBER 2003

FINAL REPORT FOR THE PERIOD 5 DECEMBER 1995 TO 15 AUGUST 2003

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TECHNICAL REVIEW AND APPROVAL

AFRL-HE-WP-TR-2003-0131

This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

//Signed//

MARIS M. VIKMANIS
Chief, Warfighter Interface Division
Air Force Research Laboratory

REPORT DOCUMENTATION PAGE

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE November 2003	3. REPORT TYPE AND DATES COVERED Final Report, 5 December 1995 - 15 August 2003

4. TITLE AND SUBTITLE

"HIGH EFFICIENCY ACTIVE MATRIX LIQUID CRYSTAL DISPLAYS (HEAMLCD)"

6. AUTHOR(S)

(a) Thomas Gunn, Rich Hicks, Wes Halstead, Charles Dionne; (b) David Craig;
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5. FUNDING NUMBERS

C: F33615-95-C-1775
PE: 62204F 62708E
PR: 2003
TA: 06
WU: 20030680

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory
Human Effectiveness Directorate
Warfighter Interface Division
Air Force Materiel Command
Wright-Patterson AFB OH 45433-7022

10. SPONSORING/MONITORING

AFRL-HE-WP-TR-2003-0131

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

20040219 097

13. ABSTRACT *(Maximum 200 words)*

This high efficiency active matrix liquid crystal display (HEAMLCD) effort examined several alternatives to increasing the total power efficiency of an AMLCD flat panel display (FPD). It was determined that the color filters passed just one-sixth of incident light and that a re-design of the addressed cell assembly (ACA) based on color separation physical phenomena represented the best new technology opportunity to improve overall display power efficiency. Current liquid crystal display (LCD) sub-pixels are covered by red, green, or blue absorptive color filters; this method discards two-thirds of available white light by structure while transmitting just 50% of the desired color. Micro-optical elements based on refractive, diffractive, or interferometric color separation, were selected for pursuit in this effort. A diffractive color separation filter (DCSF) was designed to separate the colors and focus the desired red, green, blue wavelength bands onto the subpixel apertures. The black matrix already used in AMLCD designs is used to block the spill-over of undesired wavebands from adjacent subpixels. Several prototypes of a DCSF were designed, fabricated, tested, analyzed, and reported. An alternative approach using reflective color separation (RCS) dichroic filters was also tested. Several other potential techniques for improving the efficiency of AMLCD displays, including inorganic light emitting diode (LED) backlight technology, were examined and are discussed.

14. SUBJECT TERMS
Avionics, high efficiency active matrix liquid crystal display, LCD, AMLCD, HEAMLCD, flat panel display, FPD, backlight, addressed cell assembly, ACA, absorptive filters, dichroic filters, microlens array, grating, lithography, ion etch, diffractive optics, color separation filter, DCSF

15. NUMBER OF PAGES
90

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

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FOREWORD

This contract F33615-95-C-1775 (ASTARS[1] WU[2] JON[3] 20030680) entitled "High Efficiency Active Matrix Liquid Crystal Displays (HEAMLCD)" with BAE SYSTEMS (formerly Sanders, a Lockheed Martin Company) was selected under the Air Force Research Laboratory (AFRL), then Wright Laboratory (WL), Procurement R&D Announcement (PRDA) authorized by the USAF Avionics (AV) Technology Investment Plan (TIP) No. AV95-3.02A. In the AFRL ASTARS[1] Management Information System (MIS) database the accession number is DF082384. The contract was awarded on 5 December 1995 and it ended on 15 August 2003.

Total funding to BAE SYSTEMS under this contract was $1,170,255 with sourcing as follows:

FUNDING ($) SOURCE	FY1995	FY1996	FY1997	FY1998	FY1999	FY2000	TOTALS
PE62204F/2003	46,000	654,000	250,000	0	0	0	950,000
PE62204F/2001	0	0	0	143,988	0	0	143,988
PE62708E/DARPA HDS	0	0	0	0	0	76,267	76,267
TOTALS	46,000	654,000	250,000	143,988	0	76,267	1,170,255

The Air Force was unable to complete the funding required on this effort due to the zeroing of PE62204F Task 200306 "Avionics Displays" effective 1 October 1999. In FY2000, AFRL/HECV (Dr. Darrel G. Hopper) obtained the balance needed ($76,267) from the Defense Advanced Research Projects Agency (DARPA) High Definitions Systems (HDS) program.

Dr. Hopper was the technical director for this effort from its inception in 1992 and initiated advocacy based on user requirements in 1992-3. Mr. Robert A. Michaels led the formulation of the effort in the division spend plan review in 1993. 1Lt Gretchen A. Espo served as the first Program Manager from 1994-1996 during the solicitation, negotiation, and first year of the contract. Mr. Joseph Ghrayeb served as program manager from 1997-2001 while the program was in a period of hiatus due to vendor delays. Dr. Hopper served as Program Manager from 2001-2003 to guide the review and reformulation of the effort, completion of contract execution, preparation of the final report, retirement of the casefile, and identification of new opportunities to improve AMLCDs.

This report was assembled, organized, and edited by Dr. Hopper based on the draft final report from BAE SYSTEMS dated 28 August 2003 (which comprised merely a stapling together of four prior progress reports submitted in 1999, 2001, 2002, and 2003) and on a variety of other BAE reports submitted over the period 1996-2003. [4]

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[1] A Science and Technology Activity Reporting System (ASTARS)
[2] Workunit (WU)
[3] Job Order Number (JON)
[4] This report has been formatted in accordance with the following commercial standard: "Scientific and Technical Reports—Elements, Organization, and Design," American National Standard ANSI/NISO Z39.18-1995 (NISO Press, Bethesda MD, 1995), which is available electronically at: http://www.wrs.afrl.af.mil/library/sti-pubh.htm

PREFACE

Efforts to increase the efficiency of active matrix liquid crystal display (AMLCD) technology were undertaken as a result of a 1993 survey of the Aeronautical System Center (ASC) System Program Offices (SPOs) by the then Wright Laboratory Systems Avionics Division (WL/AAA) to determine where the Lab should invest its limited exploratory research funds. Of some 132 avionics technologies suggested by the five branches of WL/AAA to the SPOs in the survey, the number one ASC choice, by far, was this high efficiency AMLCD effort. A Lab program was initiated in 1994 by the Cockpit Avionics Office (WL/AAA-2) of WL/AAA, which became the Displays Branch (WL/AAJD) of the Electro-Optics Technology Division (WL/AAJ) in FY1996, which was integrated into the Visual Display Systems Branch (AFRL/HECV) of the Crew System Interface Division (AFRL/HEC) in FY1998, which was renamed the Battlespace Visualization Branch of the Warfighter Interface Division (same office symbols) in FY2004.

The AMLCD was the first technology ever to provide sunlight-viewability video performance, as judged by pilots, but in day mode operation these first-generation avionics-grade units operated at the edge of their thermodynamic limits.[5] This problem was especially acute in the bubble-canopy fighter display designs, where sunlight-readability performance is defined as instantaneous viewability in 10,000 fc diffuse ambient illumination, while simultaneously having direct sun or a 2,000 fL specularly reflected beam of sunlight shining into the pilot's eyes. This subjective performance specification in day mode viewability translates to the objective performance specification that the display has to put out images at 200 fL (goal of 400 fL) with 10:1 contrast (goal of 50:1). Higher efficiency—i.e. less power for the same performance requirements in terms of objective image quality and end-user pilot viewability, as defined by a set of objective and subjective metrics—would increase the margin of engineering tolerance in the design of avionics addressed cell assemblies (ACA's) and of display head assemblies (DHA), and their integration into line replaceable units (LRU) for installation and maintenance in all current and future Air Force aircraft. Additional applications include Army, Navy, and commercial aircraft, spacecraft, other military needs, and, eventually, spin-off into consumer electronics applications. In this report the term liquid crystal display (LCD) means AMLCD.[6]

The high efficiency AMLCD program addresses several alternatives to increasing the total power efficiency of an avionics flat panel display (FPD). The defense need is to provide the sunlight-readability performance capability feature to pilots and other warfighters at less weight than required by the first generation avionics-grade AMLCD-based LRU, while retaining/improving the night vision system capability/compatibility performance feature.

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[5] The AMLCD is still the only display technology capable of enabling color video sunlight-readable performance. This performance is obtained by requiring several features not normally used in consumer-grade AMLCD products to be included at the various stages of manufacturing: (a) special design runs through a $2B thin-film transistor (TFT) microelectronics foundry; (b) special ACA fabrication steps; (c) special DHA fabrication steps; and (d) special LRU design steps. Avionics-grade AMLCDs result from this process, but the underlying AMLCD technology is still in need of improvement to meet the performance goals, rather than the performance minimums, established by task-based human factors studies for cockpits and other applications requiring sunlight readability. Recently, the avionics industry has begun to experiment with miniature AMLCDs in a projection design; one promising approach uses miniature reflective AMLCDs fabricated on silicon substrates, rather than on the usual glass substrates; this variation of AMLCD technology is known as liquid crystal on silicon (LCOS).

[6] The acronym LCD has come to mean "large-area transmissive a-Si TFT AM LCD" unless stated otherwise.

The first-generation avionics-grade AMLCDs consumed less power than mature avionics-grade CRTs while providing dramatically superior image content and sustainability (30X less cost). However, further power reductions were desired. For example, the F-15 aircraft had reached its on-board power generation limits in 1995 when this contract began.

During the 1990's the avionics-grade AMLCD became the strongly preferred technology for all aircraft cockpits in every new and legacy aircraft program on the planet: military, commercial, and general aviation. The first new military aircraft to commit to AMLCD was the FA-22A program in 1992. Also in 1992, the Boeing company committed the B-777 cockpit to AMLCD—the first new commercial livery program to do so. During the 1990s and continuing during the 2000's all legacy aircraft have undertaken programs to replace flight instruments and multifunction displays based on older technologies, including electromechanical (EM) and CRT, with AMLCDs. Pilots prefer AMLCDs because they have dramatically superior performance in terms of sunlight readability, full-screen color video images, better night vision compatibility, and their ability to produce "steady" images without flicker. Maintainers prefer avionics AMLCDs because they have mean time between failure (MTBF) rates of 10,000 to 30,000 hrs of operation as compared to the typical 300-800 hrs afforded by either EM or CRT-based units. And AMLCDs cost less as long avionics display suppliers to aircraft programs have cut deals to gain reliable access to purchase time on $2B-capitalization TFT fabrication facilities.

The F-117A aircraft, pictured below, was the first military aircraft to commit to the use of AMLCD technology in an operational cockpit; this first avionics-grade display was a 4.75 x 1 in. monochrome amorphous silicon (a-Si) thin-film transistor (TFT) AMLCD display installed in the head-up display (HUD) control panel. Subsequent programs have and are updating the monochrome green CRTs in the main instrument panel to be updated to avionics-grade color video a-Si TFT AMLCD technology. An AFRL schematic of an avionics-grade AMLCD is provided below to orient the reader to the technology.

**First Military Avionics-Grade TFT AMLCD
Installed in Operational Cockpit (circa 1990)**
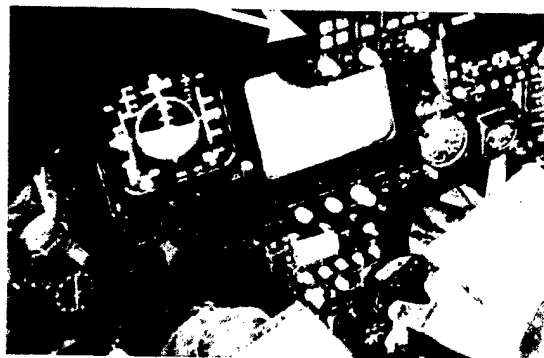
Schematic of Avionics AMLCD
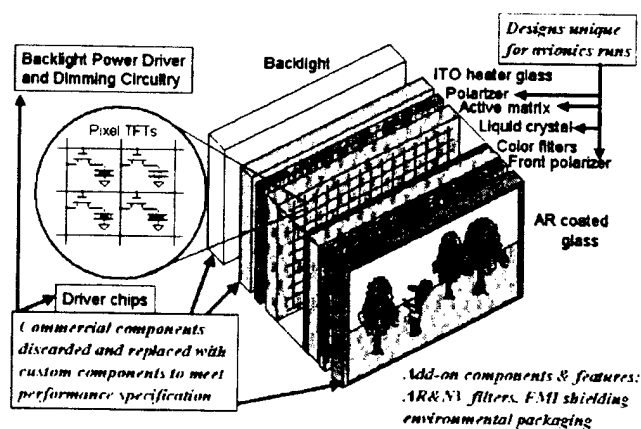
To initiate AFRL activity in response to the above-described SPO survey a contract for the presently reported extramural contractual effort was awarded on 5 December 1995 to Sanders Avionics, a Lockheed Martin Co. (LM Sanders), which was purchased by BAE SYSTEMS in November 2000. The research was performed at BAE SYSTEMS in Nashua NH (BAE Nashua) and Edinburgh, Scotland, United Kingdom (UK) (BAE Edinburgh), and at the facilities of a key subcontractor, MEMS Optical Inc. in Huntsville AL.

The overall objective of the effort F33615-95-C-1775 reported in this document was to investigate ways to improve the efficiency of macroelectronic TFT liquid crystal displays (LCDs) by exploring the technical feasibility of using non-absorbing optics to perform the color separation function in a color LCD while meeting or exceeding current TFT AMLCD performance and operational goals. All micro-optical technologies that could meet the stated objective were reviewed and selected approaches were pursued. Important contract milestones were as follows:

1995 Contract award date 5 December 1995
1996 Proposed Active Color Separator (ACS) approach based on refractive microlens arrays discarded
1997 Fabrication capability evaluation tasks from Sanders to DOC & SY (each made 1x1 in. test devices)
1998-1999 First iteration DCSF design, fabrication, evaluation, and demonstration by SY/MEMS
1999-2000 Delays due to problems regarding equipment used by SY/MEMS to fabricate DCS filters
and due to BAE SYSTEMS purchase of Sanders Avionics from Lockheed Martin
2001 Second iteration ICSF design, fabrication, evaluation, and demo by MEMS and BAE Nashua;
BAE Nashua drops displays work; BAE Edinburgh in U.K. recommended by AFRL (Dr. Hopper);
2002 Transfer of Avionics Displays & Principal Investigator duties to BAE SYSTEMS in Edinburgh U.K.
Review of program, DCS progress & recommendation of other approaches by BAE Edinburgh U.K.
2003 Staff reductions at BAE Edinburgh; Display expertise reconstituted at BAE Nashua;
Evaluation of dichroic color filter approach by BAE Nashua;
Contract end date 15 August 2003

The core challenge addressed under this contract was met: breadboard diffractive color separation filters (DCSF) were designed, built and tested, and a dichroic color filter approach was evaluated, to identify the technical barriers and opportunities to the removal of color filters from AMLCDs.

Filter fabrication and institutional issues (that could not have been anticipated) turned a 3-year planned contract into an 8-year effort. Unexpected technical challenges associated with materials, processes, and tooling by DCSF fabrication subcontractors, together with time delays imposed by the purchase and reorganization of Lockheed Martin's (LM) Sanders Avionics Division in Nashua NH by BAE SYSTEMS in late 2000, and additional time delays in 2001-2002 occasioned by the need to obtain a export license and Technical Assistance Agreement (TAA) from the U.S. Departments of State and Defense to perform a key task at BAE SYSTEMS in Edinburg UK, resulted in completion of the program on 15 August 2003 rather than in FY99 as originally planned at contract award in early FY96.

ACKNOWLEDGEMENTS

HIGH EFFICIENCY ACTIVE MATRIX LIQUID CRYSTAL DISPLAYS (HEAMLCD)

1. SUMMARY

This extramural High Efficiency Active Matrix Liquid Crystal Display (HEAMLCD) contractual effort examined several alternatives to increasing the total power efficiency of an AMLCD flat panel display (FPD). A schematic diagram of a typical liquid crystal display (LCD) is shown in Figure 1. It was determined that the color filters passed just one-sixth of incident light and that a re-design of the addressed cell assembly (ACA) in Figure 1, based on color separation physical phenomena, represented best new technology opportunity to improve overall display power efficiency. Optical diagrams, or stack ups, of the ACA and absorptive color filter are illustrated in Figure 2, where the active matrix (AM) backplane feature of the AMLCD is implemented by a thin-film transistor (TFT) array fabricated on the back plate of the LCD before cell assembly. Current color LCD sub-pixels are covered by red, green, or blue absorptive filters; this method discards two-thirds of available white light by structure while transmitting just 50% of the desired color.
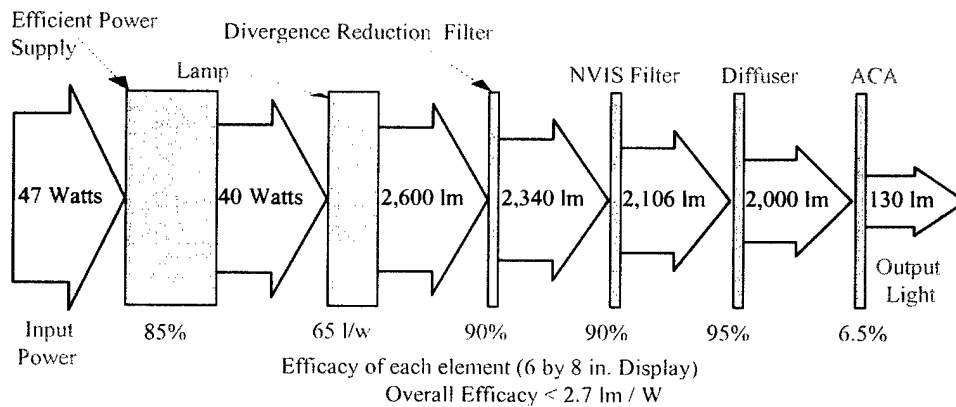
Figure 1: Schematic of optical components comprising traditional LCD
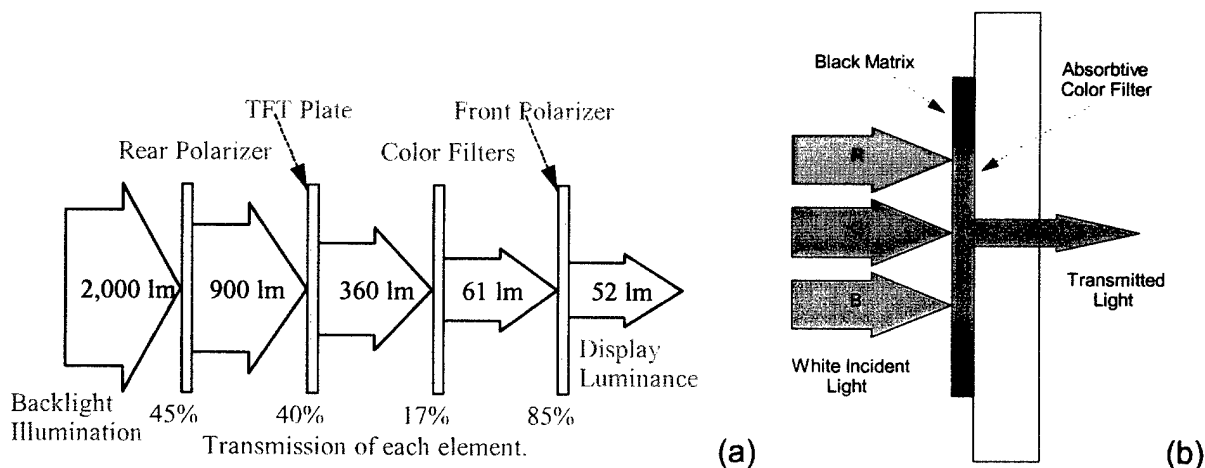
Figure 2: (a) Addressed cell assembly (ACA) in TFT AMLCD; (b) absorptive color filter

Micro-optical elements based on refractive, diffractive or interferometric, diffractive color separation (DCS) were selected for pursuit in this effort. A diffractive color separation filter (DCSF) was designed to separate the colors and focus the desired red, green, blue wavelength bands onto the subpixel apertures. The black matrix already used in AMLCD designs is used to block the spill-over of undesired wavebands from adjacent subpixels. Several prototypes of a DCSF were designed, fabricated, tested, analyzed, and are reported.

The program resulted in prototype designs for a DCSF as illustrated in Figures 3 and 4. Mathematical modeling showed the design was valid. Early on it was ascertained that materials, processes, and tooling might limit capabilities produce the DCSF because the high aspect ratio of features required by the design were at the outter-edge of state-of-the-art diffractive optics fabrication technology. Both analog and discrete designs were considered, as illustrated in Figure 5. Significant progress was made in the development of new materials and techniques, and in the design, building, and testing of new diffractive optic fabrication tools. Unfortunately, the fabrication techniques and tooling were not capable faithfully rendering the mathematical design with sufficient fidelity. The layout of typical AMLCD pixels is illustrated in Figure 6. Figure 7 shows the proposed AMLCD re-design using DCS micro-optical elements.

(a)   (b)
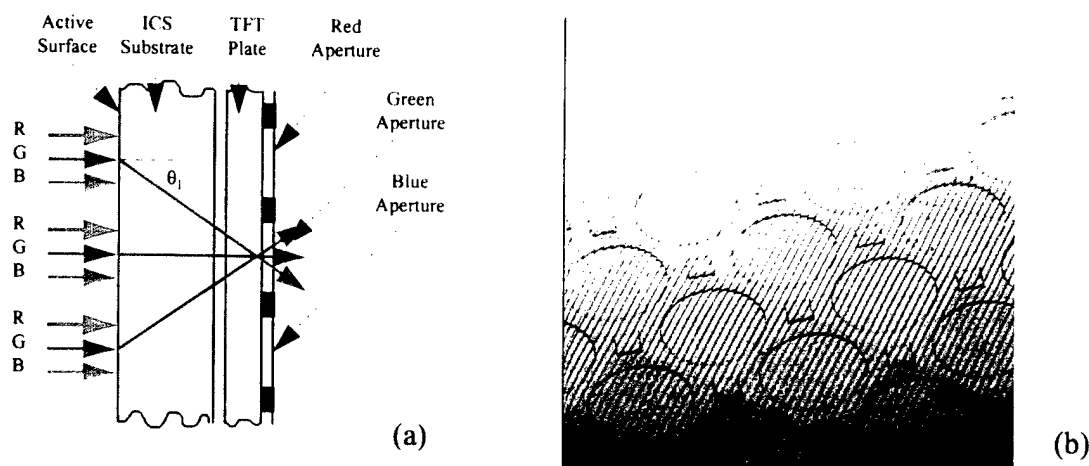
Figure 3(a): Concept of the inteference-based diffractive color separation (ICS = DCS) filter;
Figure 3(b): SEM photo of 2nd iteration DCSF fabrication by SY/MEMS (November 1998)

Blue   **Green**   **Red**
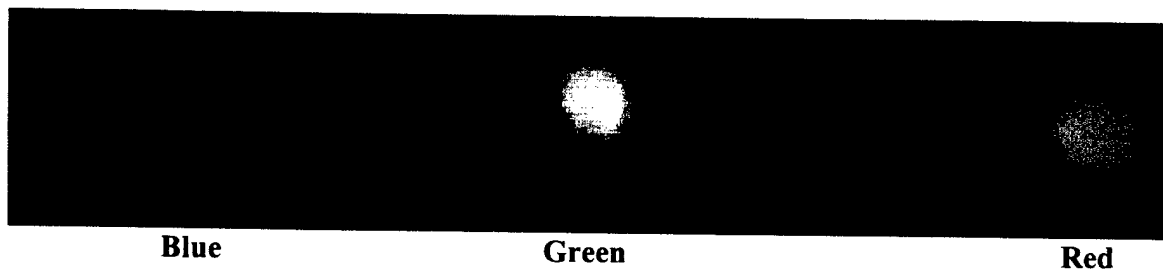
Figure 4(a): Color separation detected on SY Technologies DCS analog mask ICS1 (February 1998)
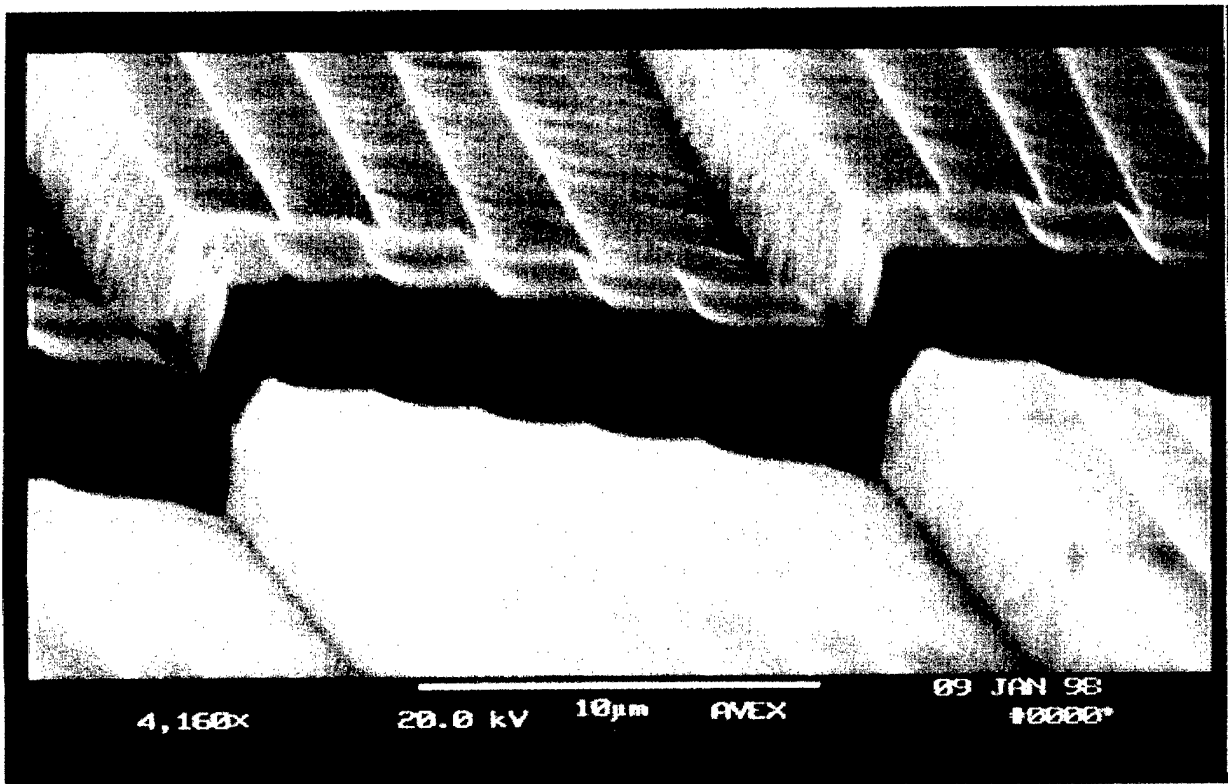
Figure 4(b): Scanning electron micrograph (SEM) of DCS analog mask ICS1 (January 1998)
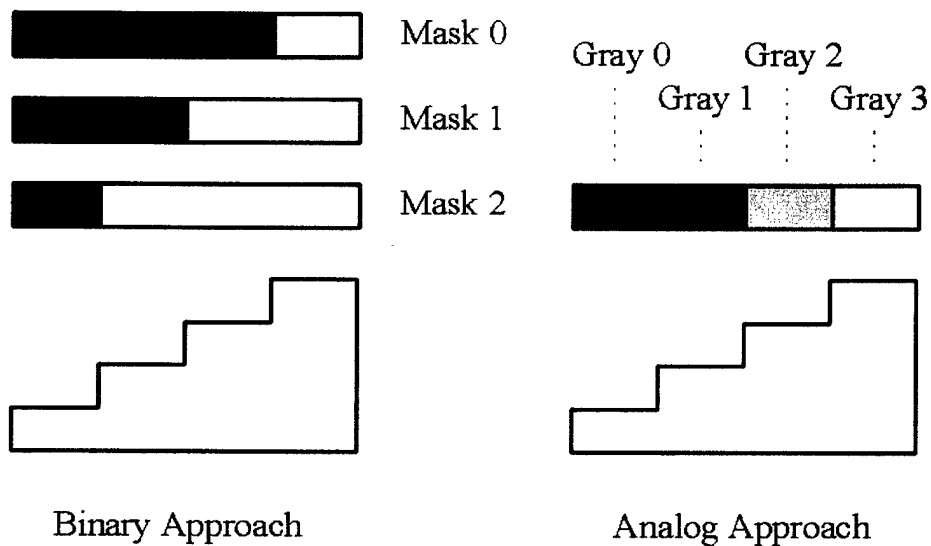
Figure 5: Binary and analog approaches to micro-optical element fabrication involving an optical mask, photoresist, and etch process to fabricate the initial part (or master) from which copies are produced by a stamping process
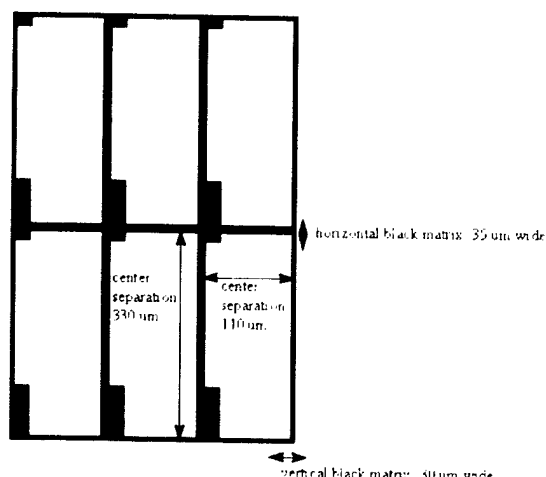
Figure 6: Dimensions of pixels and black matrix in a typical AMLCD

Color AMLCD design typically involves spatial red, green, and blue subpixels. For example, in Figure 6 a square 330 x 330 μm color pixel comprises three adjacent 110 x 330 μm subpixels. Light is generated by a white lighting system (usually from back). Traditional AMLCD cell fabrication places red, green and blue absorptive filters on each set of three adjacent subpixels. The current effort addresses the technical challenges of replacing these absorptive color filters with diffractive color separation filters.

The black matrix in Figure 6 covers the TFTs (corners) and addressing lines (30-35 μm) to prevent reflections and photovoltaic currents from both ambient and back light.

Efficiency of each element (6 x 8 in. Display)
Overall Efficiency > 14.5 lm / W
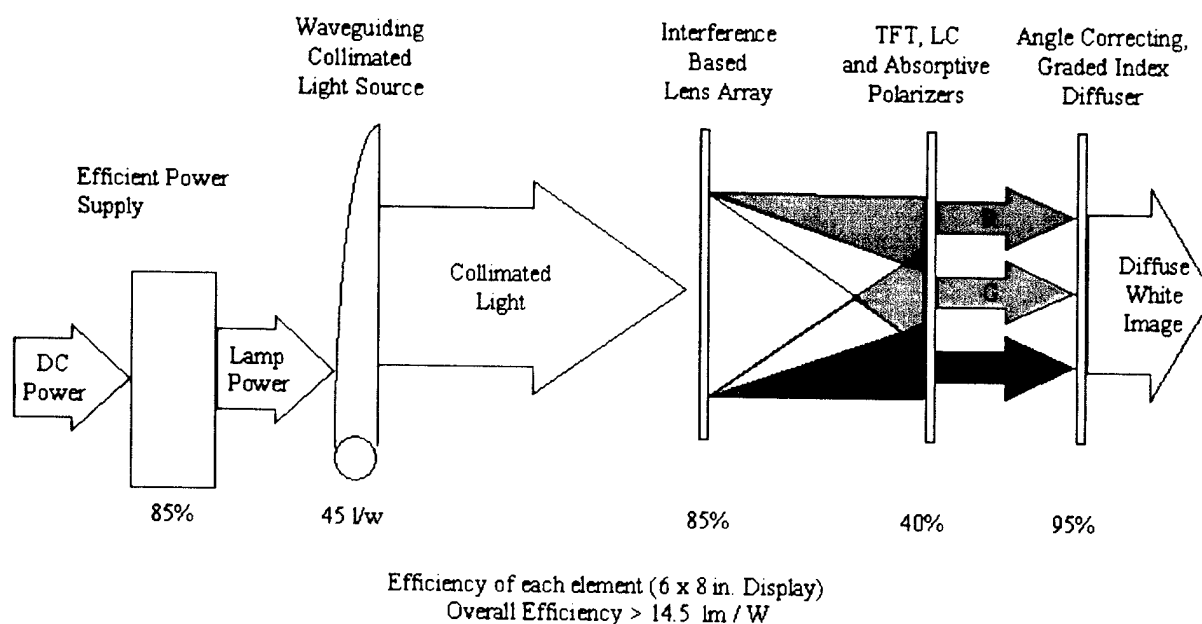
Figure 7: Proposed overall AMLCD re-design using DCS intererence-based lens array

Performance actually achieved for breadboard DCSF's is detailed in the report. Opportunities to overcome the remaining diffractive optic fabrication technology challenges are identified. An alternative approach using dichroic filters was also tested, but was found unlikely to be as attractive from a systems engineering perspective as the DCSF approach. Several other potential techniques for improving the efficiency of AMLCD displays were examined and are discussed.

2. INTRODUCTION

2.1 Overview

Over the first several years of the program various technologies were reviewed. Research results from December 1995 through 1998 are reported in a series of four publicly available papers, which are listed with full reference information in Appendix B.

In 1998 BAE SYSTEMS determined that MEMS Optical Inc., a unit of SY Technologies Inc. located in Huntsville AL, had the highest potential of developing a color separator element that would meet the objectives of the program; a subcontract was subsequently awarded. MEMS Optical had two additional positive features: MEMS Optical was one the few U.S. companies doing research in this area (making it possible for rapid technology evaluation iterations with the BAE team in Nashua); and MEMS Optical was willing to use its own capital funds to build the foundry and to create the needed new process technology. It took MEMS Optical several years to complete their foundry and put in place a process to complete the color separator. During that time BAE SYSTEMS continued to investigate other technologies that might achieve the program objective but none proved as promising as the diffractive color separation filter (DCSF) approach whose fabrication was being pursued via the MEMS Optical subcontract.

Sections 3.1.1, 3.1.2, 3.1.3 and Appendix C present the methods, results and discussion of the very extensive research performed by Messrs. Peter S. Erbach, Greg T. Borek, and David R. Brown of MEMS Optical Inc. under its subcontract from mid-1997 through August 2001. Section 3.1.4 presents the methods, results, and discussion of experiments conducted by Charlie Dionne in December 2001 through March 2002 at BAE SYSTEMS Nashua to evaluate the performance of the best MEMS color separator optical elements. Section 3.2 presents an alternative approach based on inorganic light emitting diodes (LEDs). Section 3.3 presents a complete review, covering the period December 1995 through October 2002, performed by Mr. David Craig of BAE SYSTEMS Edinburgh U.K.; this review includes an evaluation of current opportunities for increasing avionics AMLCD efficiency and recommendations for specific activities to complete this effort consistent with the contract statement of work (SoW). Section 3.4 presents work performed in 2003 by Mr. Tom Gunn of BAE SYSTEMS Nashua, based on a recommendation by Mr. Craig, to examine an alternative approach based on dichroic filters.

Patents issued based on work performed under this contract are listed in Appendix A.

2.2 Statement of Work

2.2.1 Scope. Paramount to the HEAMLCD program was the reduction of power required for generating an image of sufficient luminance for viewing under high ambient illumination conditions. To this end BAE was to redesign several optical components in an LCD "stack-up" to employ non-absorptive techniques while maintaining the same level of display performance. While the program recognized the importance of proper cooling design, mechanical packaging, and interface and support electronics, the program focused on the development of an electro-optical demonstration with minimal support electronics and packaging.

2.2.2 Objective. The overall objective of the HEAMLCD program is to prove the technical feasibility of using non-absorbing optics to perform the color separation function in a color LCD while meeting or exceeding current AMLCD performance and operational goals, and at the same time, demonstrate key power, cost, and reliability improvements to current and future display programs.

2.2.3 Phase 1 – Technology Development. The primary purpose of Phase 1 was to develop the technology necessary to design and fabricate components of the demonstration system as well as to plan for the fabrication and integration of a demonstration display. The requirements to be met by BAE SYSTEMS as the contractor during Phase 1 were as follows:

"The contractor shall develop interface, performance, and test requirements for each of the demonstration components. The requirements shall be traceable to the system goals of power reduction or performance enhancement and the component builds in the following phases.

"The contractor shall provide detailed designs for each of the components developed in support of Phase 2. The contractor shall fully identify the engineering risk/complexity and cost involved in the production of each of the components.

"The contractor shall fabricate and test samples of each of the components designed in the previous task. This task shall be iterative with the design task, both being complete upon the realization of successful test results.

"The contractor shall develop a plan for the integration of each of the components into a display system for the next phase (Phase 2) of the program. The plan shall include necessary procedures and process controls for the successful integration of the components into a demonstration display system. The identification of these procedures shall include risk, cost, and engineering analysis necessary to support not only the demonstration integration, but also a plan for the transition of this technology to a current or future display production program."

2.2.4 Phase 2 – Demonstration Integration. The purpose of Phase 2 was to build and test a demonstration display that verified the predicted interaction of components developed and tested as part of Phase 1. The requirements to be met by BAE SYSTEMS as the contractor during Phase 2 were as follows:

"Component Fabrication: The contractor shall fabricate and test the components developed in

phase 1 in the quantities required for the assembly of at least one demonstration display. The components shall be fabricated in accordance with the design documentation developed as part of tasks in phase 1.

"ACA Integration: The contractor shall fabricate a liquid crystal display for the demonstration display. The contractor shall integrate the optical components into the LCD according to procedures and process controls developed in phase 1. The contractor shall also integrate the necessary electronics with the LCD to form an Addressed Cell Assembly (ACA.) The contractor shall test and document the performance of the ACA.

"Demonstration Integration: The contractor shall fabricate the hardware necessary for placing test images on the ACA developed in the previous task. This hardware shall be integrated with the ACA to form a stand alone display demonstration system. This system shall be for use in a laboratory environment only and may require special shipping containers as deemed necessary. Special shipping containers, as required, shall be constructed as part of this effort.

"Demonstration Test and Documentation: The contractor shall test the optical performance of the demonstration display and document the test results for inclusion in the final report. The tests shall include, as a minimum: luminance, contrast, color saturation, and luminance uniformity. The contractor shall document the results of the tests in Presentation Material and present them at a System Design Review (SDR)."

2.3 DCS Theory of Operation

The theory of operation for the DCS filters is illustrated in Figures 7(a) and 7(b). The DCSF is designed so that the red light propagates through to the −1 order as shown in Figure 7(a) and passes through the subpixel (color-stripe) of an LCD color pixel addressed with red data as shown in Figure 7(b). The green light propagates to the 0 order and passes through the subpixel addressed with the green data in the LCD color pixel, and the blue light propagates to the +1 order and it passes through a sub-pixel addressed with blue data.

(a)

(b)
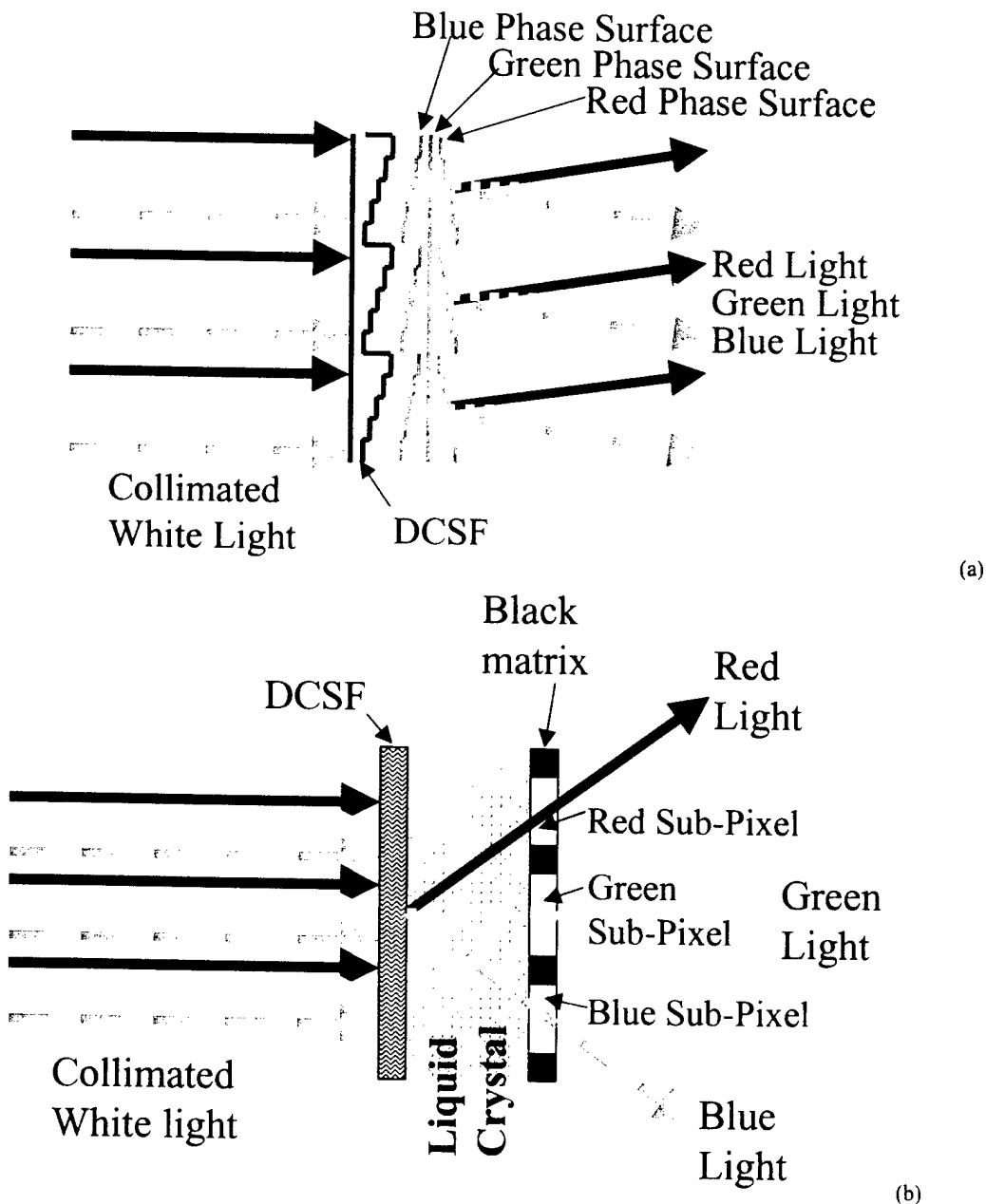
Figure 8. DCSF theory of operation

3. METHODOLOGY, RESULTS, AND DISCUSSION

3.1 Optical Diffractive Interference Color Separation Filter (DCSF or ICSF) Fabrication

3.1.1 Evaluation of DCS Filter Design Approaches in 1 x 1 in. Test Size (April 1998)

The first fabrication of the diffractive interference color separation filter (acronym: DCSF or ICSF) was in proof-of-capability sizes (e.g. 1 in.). In 1997 BAE SYSTEMS Nashua (then LM Sanders Avionics) tasked both the Digital Optics Corporation (DOC) and SY Technologies with the idea of down selecting for full display-size component fabrication.

The test phase fabrication task results from DOC were submitted to LM Sanders in a six-page report assembled by Dr. Thomas J. Suleski dated 30 December 1997. DOC successfully fabricated its version of the 1 x 1 in. ICSF device and presented qualitative performance tests confirming color separation and focusing operations of their component. However, the DOC measurements were very qualitative in nature: the light source spectral composition and degree of collimation were unknown; and the widths and clarity of the color bands varied substantially.

The color separation achieved by SY in March 1998 is illustrated in Figure 9. In April 1998, LM Sanders selected SY as their vendor to continue research and fabrication of DCS filters, including a planned full-size 6 x 8 in. DCS filter for integration by Sanders with an AMLCD. All fabrication was accomplished by SY Technologies and its MEMS Optical Inc. manufacturing subsidiary, established April 1998, in Huntsville AL (acronyms SY, MEMS, and SY/MEMS).
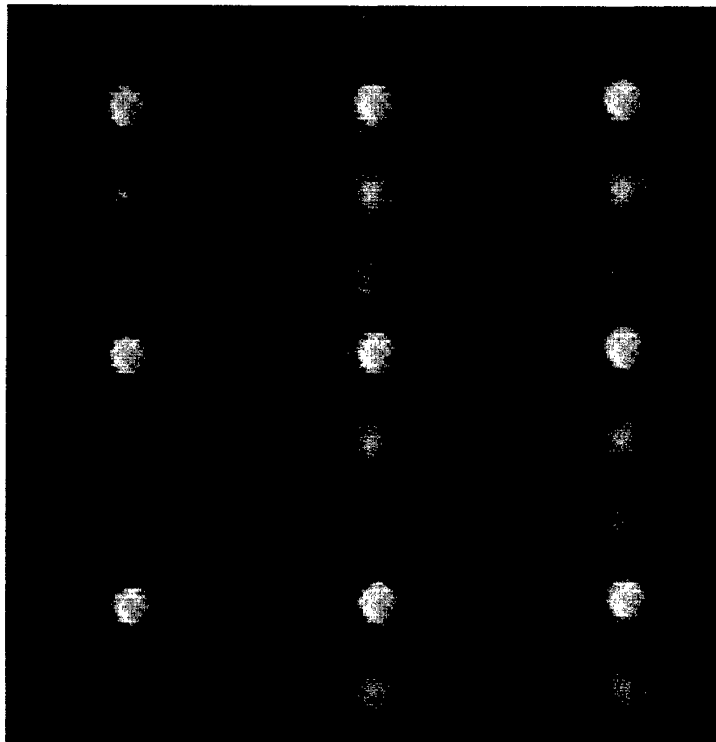
Figure 9: ICSF results using 2X grating-lens combination in SiO_2 (SY Try5, March 1998)

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The results of two iterations of component fabrication at SY/MEMS for a full-size display are presented in section 3.1.1 and Appendix C (1998 results), section 3.1.2 (1999 results), and section 3.1.3 (2001 results). These two "iterations" are also referred to by SY/MEMS as their "Phase I and Phase II" efforts. The BAE Nashua evaluation (March 2002) of the final MEMS results is presented in section 3.1.4. Recommendations from MEMS Optical (August 2001) are presented in section 5.1.

Results on work to design, fabricate, and test DCS filters by MEMS Optical and BAE Nashua obtained from April 1998 to December 1998 were summarized in detail in a paper presented at the SPIE Photonics West Symposium in January 1999, and subsequently published in the Proceedings of SPIE Volume 3636; this SPIE paper is included as Appendix C of this report.

3.1.2 Initial Full-Size Display MEMS Designs and Tests of DCS

3.1.2.1 First High Index Material Binary and Grayscale Gratings (April 1999). The first decent lot of binary and grayscale gratings were fabricated by SY Technologies in April 1999 as illustrated in Figure 10. Figure 10(b) shows an isometric, or three-dimensional (3D), view of an atomic force microscope (AFM) surface scan of the DCSF made in a high index material (HIM), namely tantalum oxide, Ta_2O_5. Figure 10(a) shows a two dimensional (2D) AFM scan of the DCSF surface; there are only two step heights shown in this particular scan: 440.32 and 467.66 nm. The bottom step is around 350 nm. This scan limitation to two step heights appears to be due to accumulation of mask alignment errors near the main edge. However, the average step height is about 460 nm, which is appropriate for green light in the Ta_2O_5 material. This was the first decent shot at fabrication of the DCSF in a decent batch of the Ta_2O_5 material. The achievement of this milestone enabled MEMS Optical to start refining the DCSF fabrication processes and to add the lens functionality envisioned by the DCSF design.[7]

Grayscale filter (photoresist) results achieved in April 1999 are illustrated in Figures 11-13.

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[7] The DCS filters were designed as a convolution of multiple optical functions.

Multilayer Filter
(Etched)

Section Analysis

L	1.953 µm
RMS	267.82 nm
lc	DC
Ra(lc)	152.64 nm
Rmax	653.23 nm
Rz	653.23 nm
Rz Cnt	2

Spectrum

Surface distance	9.518 µm
Horiz distance(L)	7.969 µm
Vert distance	2.212 µm
Angle	15.516 deg
Surface distance	1.965 µm
Horiz distance	1.719 µm
Vert distance	440.32 nm
Angle	14.369 deg
Surface distance	2.547 µm
Horiz distance	1.953 µm
Vert distance	467.66 nm
Angle	13.466 deg
Spectral period	DC
Spectral freq	0 Hz
Spectral RMS amp	0.010 nm

greg1.01

Cursor: moving Zoom: 2:1 Cen line: Off Offset: Off

Figure 10(a): Multilayer filter greg1.01 – AFM 2D scan showing steps of 440.32, 467.66 nm.

Multilayer Filter
(Etched)
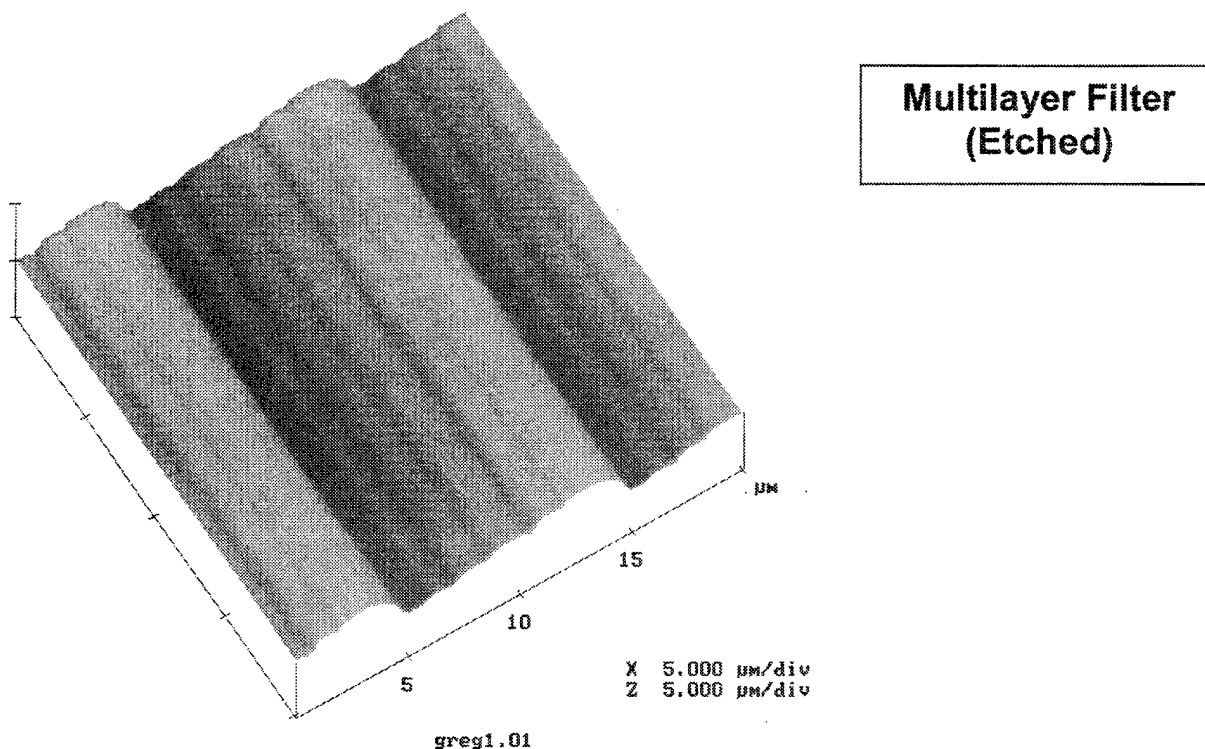
greg1.01

Figure 10(b): Multilayer filter greg1.01 etched in Ta_2O_5 -- AFM 3D surface scan (April 1999)

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Section Analysis

Grayscale Filter (Photoresist)

nm

L	1.563 µм
RMS	96.322 nm
lc	DC
Ra(lc)	20.618 nm
Rмax	91.973 nm
Rz	90.440 nm
Rz Cnt	2
Radius	3.577 µм
Sigмa	15.585 nm

0   5.0   10.0   15.0
µM

Spectrum

Surface distance   1.598 µм
Horiz distance   1.563 µм
Vert distance   256.62 nm
Angle   9.327 deg

DC   Min

csep_gra.000

Cursor: fixed   Zoom: 1:1   Cen line: Off   Offset: Off
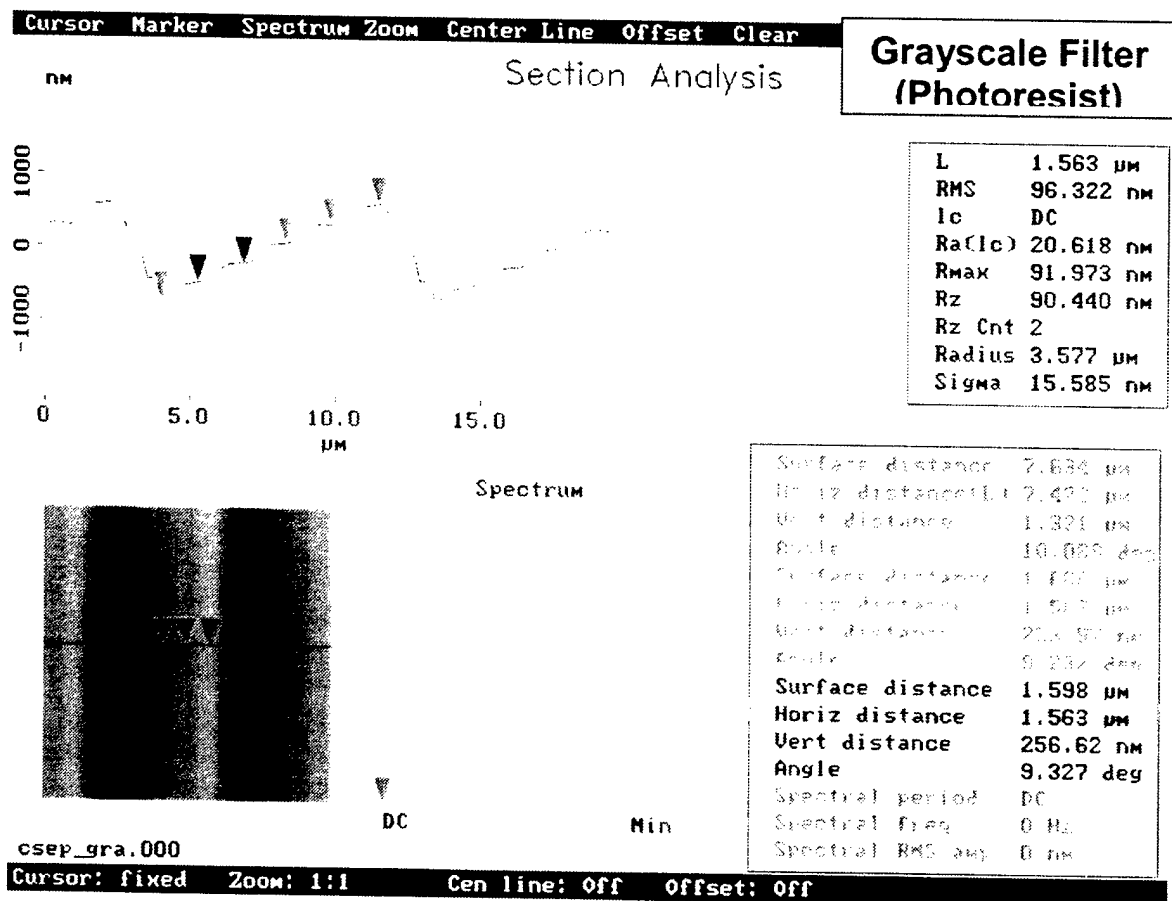
Figure 11(a): Grayscale filter csep_gra.000 – AFM 2D scan showing steps of 253.97, 256.62 nm

Grayscale Filter (Photoresist)

5   10   15   µм
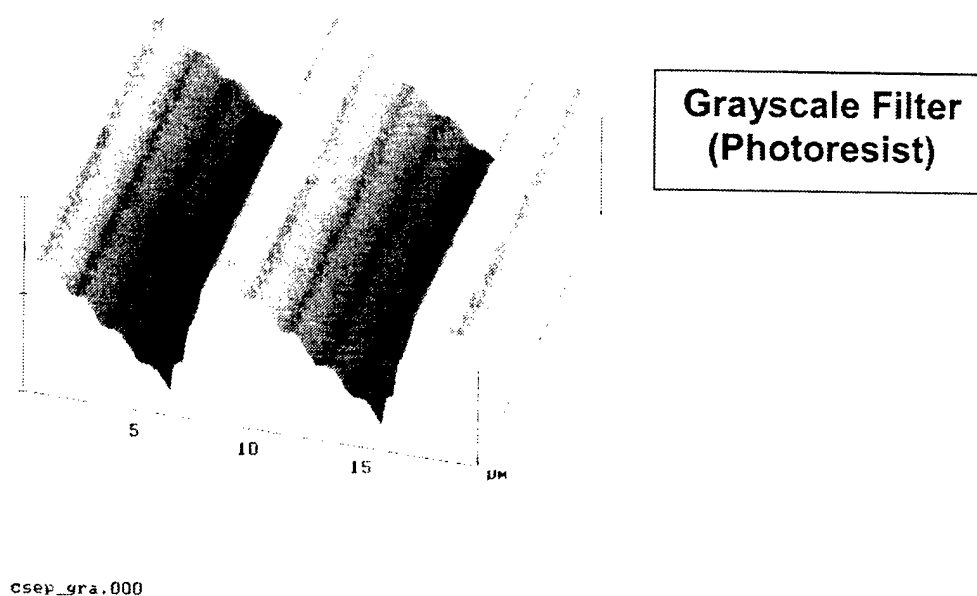
csep_gra.000

Figure 11(b): Grayscale filter csep_gra.000 – AFM 3D surface view (April 1999)
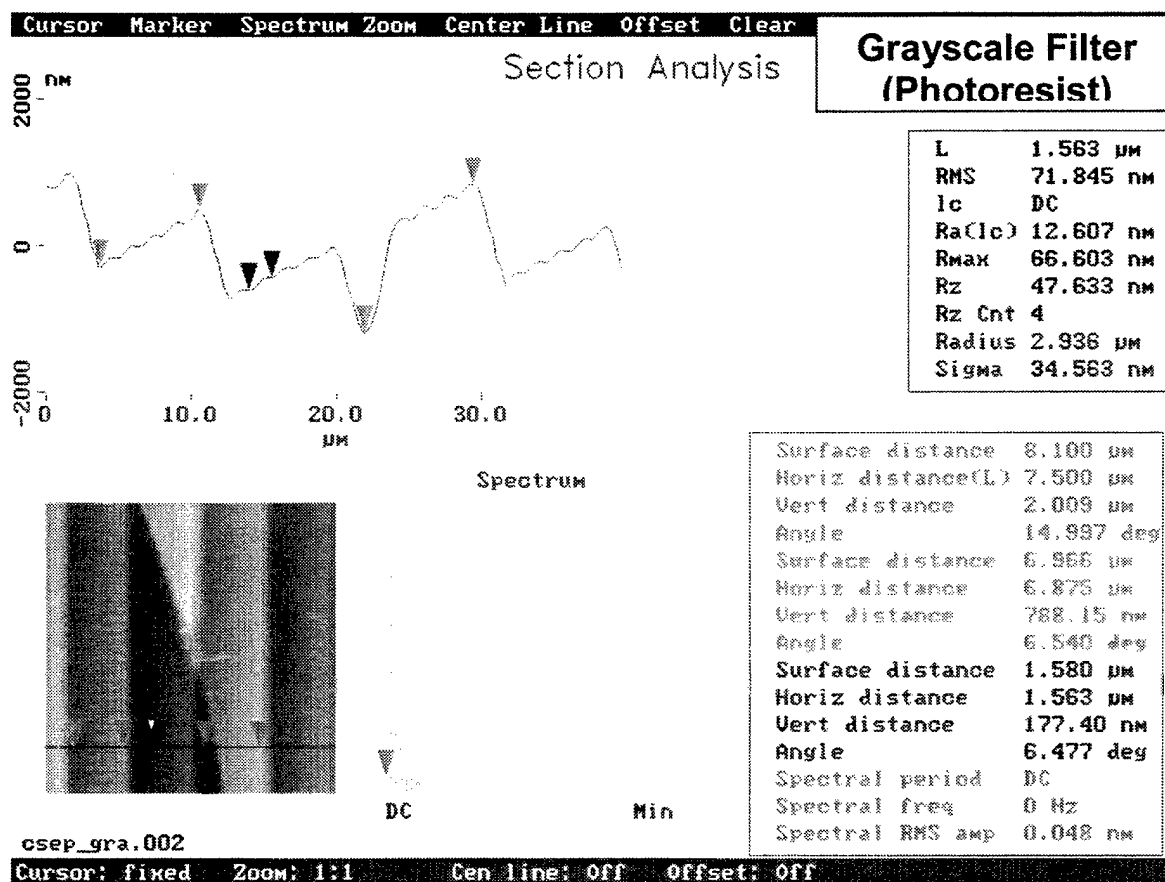
Figure 12(a): Grayscale filter csep_gra.002 – AFM 2D scan showing steps of 788.15, 177.40 nm
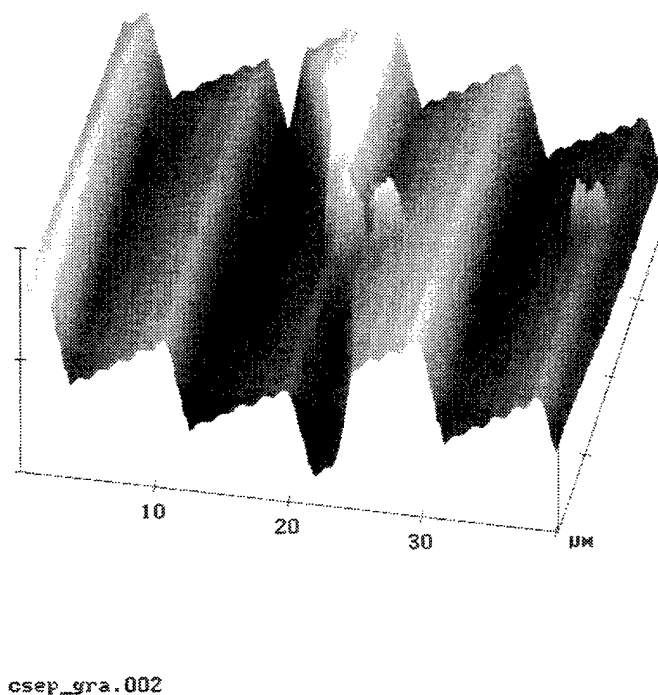
Figure 12(b): Grayscale filter csep_gra.002 – AFM 3D isomeric surface view (April 1999)

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Grayscale Filter (Photoresist)

X   20,000 µм/
2   5000.000 n
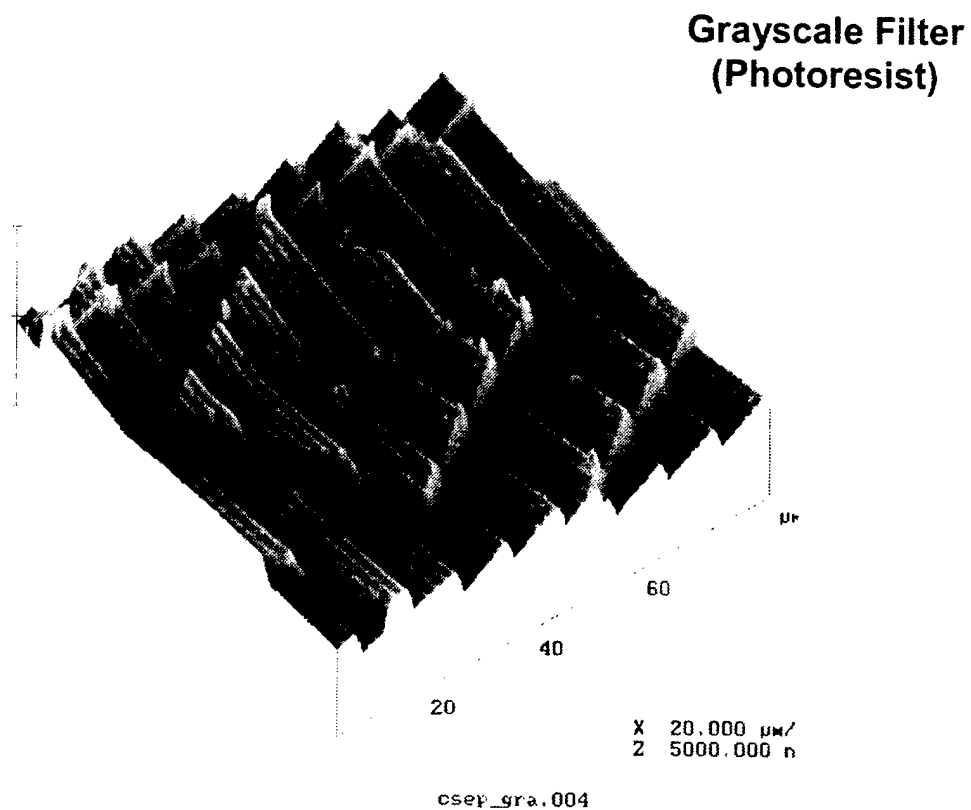
csep_gra.004

Figure 13(a): Grayscale filter csep_gra.004 – AFM 3D surface view, perspective one (April 1999)

µм

X
Z
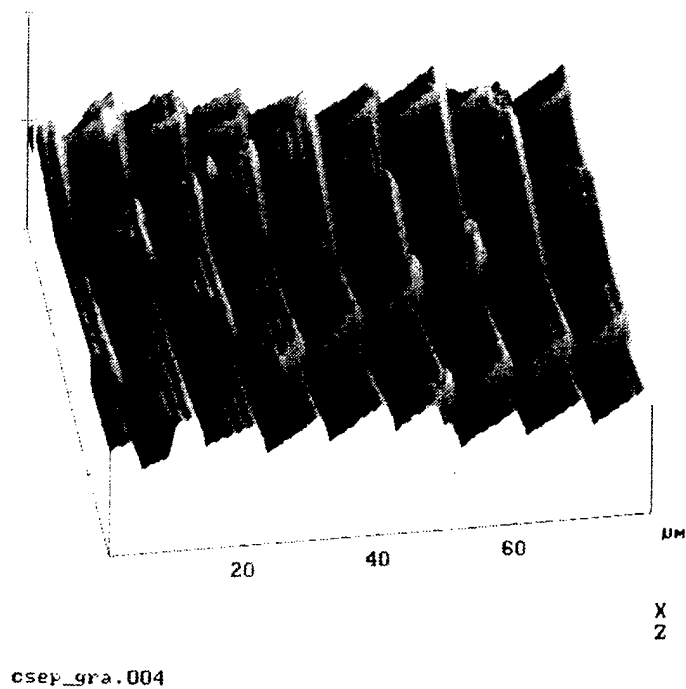
csep_gra.004

Figure 13(b): Grayscale filter csep_gra.004 – AFM 3D surface view, perspective two (April 1999)

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3.1.2.2 Improved High Index Material Gratings (August 1999). The first HIM grayscale etch results were reported by MEMS Optical on 18 August 1999. Thicker photoresist was used than previous multi-task (integrated grating-lens) attempts, which caused a good deal of redeposition of chamber reactants.

The third HIM part grayscale etch results yielded a good quality part, as illustrated in Figure 14, but with a selectivity of 1, compared to a desired selectivity of 2. These parts were obtained by increasing both the O_2 and CHF_3 concentrations. Increasing CHF_3 with the same O_2 flow yielded a fourth part, also of good quality, but with selectivity increased slightly to about 1.1.

Issues and problems affecting the high index coating results achieved by MEMS in the Summer of 1999 were: (a) surface cleanliness; (b) evaporation rate; (c) thickness; and (d) chilled water.

3.1.2.2.1 Surface Cleanliness. The glass was cleaned in a vapor degreaser then an ultrasonic cleaner before being moved to the coating area. Parts were then cleaned again in the coating area before being loaded into the coating chamber. Parts described in this section (August 1999) may have sat too long after the ultrasonic cleaning step before being moved into the coating area, which may have resulted in contaminants that could not be thoroughly removed during the finishing cleaning before coating.

3.1.2.2.2 Evaporation Rate. The last lot of material (five coating runs in April 1999) were run at an evaporation rate of 5-6 (arbitrary units). The new parts (August 1999) were run at a lower evaporation rate of 3-5.

3.1.2.2.3 Thickness of Photoresist. The greater thickness of the photoresist resulted in surface stress. The thickness for the April 1999 lot was 6 μm; the thickness for the August 1999 lot was 5.1 μm.

3.1.2.2.4 Chilled Water. Diffusion pumps for all MEMS coating chambers were cooled with a chilled water system. Several weeks of extreme heat in Huntsville AL during the Summer of 1999 may have caused "soft" coatings in coating chambers. This situation was first noticed on or about 4 August 1999 after the parts had been processed. It was estimated that this situation probably became progressively worse during the period 18 June 1999 to 18 August 1999. An analysis of the problem traced to the chilled water system as not being able to cool enough in the hot environment. It was noted that as diffusion pumps get too hot, they back contaminants into the coating chamber. As noted above, a good deal of redeposition of chamber reactants was observed. The chilled water system was modified by 13 August 1999 for operation on extremely hot days.

Another batch of HIM parts was planned to be shot on 23 August 1999 that was to have had a better chance to obtain better selectivity.

Profile of metrology area showing average step height Note: Images are contrast and brightness enhanced
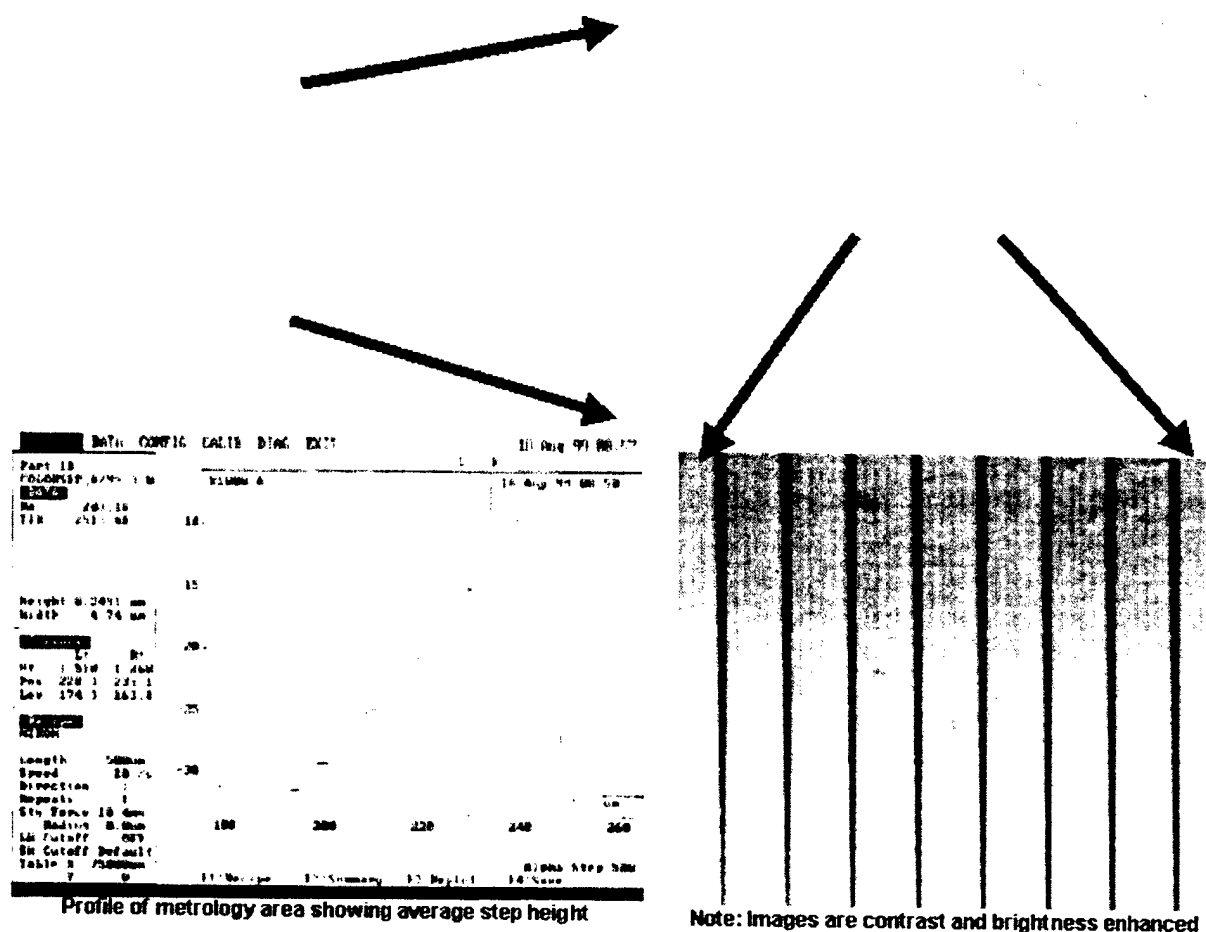
Figure 14. Grayscale etch in high index material, selectivity ~1.1 compared to desired = 2
(MEMS Part No. 3, 18 August 1999)

3.1.3 Final MEMS Tests, Comparisons with Previous Designs (August 2001). Equipment problems delayed progress at MEMS Optical from September 1999 to August 2001. The final results from SY/MEMS were submitted to BAE Nashua in a report dated 30 August 2001. The report was authored by Dr. Peter S. Erbach of MEMS Optical. These most recent etch results are presented and compared in this section 3.1.3 with those from previous efforts in 1998 and 1999.

Previous tests employed two different designs. Each design utilized the same basic structure. The designs are different in their feature size and focusing elements. DCSF design #1 has features that are half the size of the features in design #2. These designs are called 1X and 2X, respectively. Design #1 contains no focusing elements and design #2 contains refractive lens element for focusing the desired color band through the designated color stripe of each LCD pixel. The "1X" (high frequency grating) design with grating-only is etched into a Corning 1737 substrate coated with high index material. The "2X" (low frequency grating) tilted design with the grating-lens combination is etched into an SiO_2 substrate. The test configurations used are illustrated in Figure 15(a) for the "1X" design and in Figure 15(b) for the "2X" design.
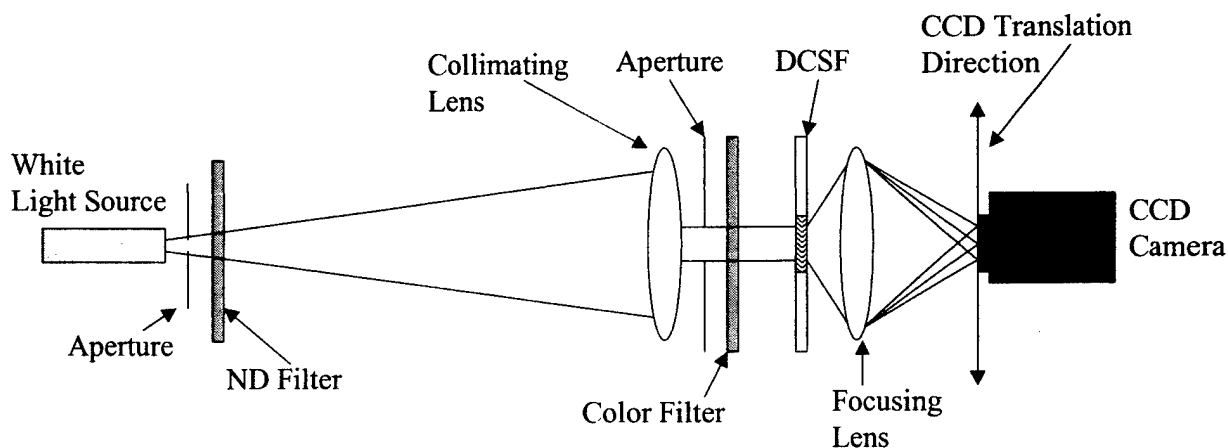
Figure 15(a). Test configuration for the 1X (grating only) DCSF design.
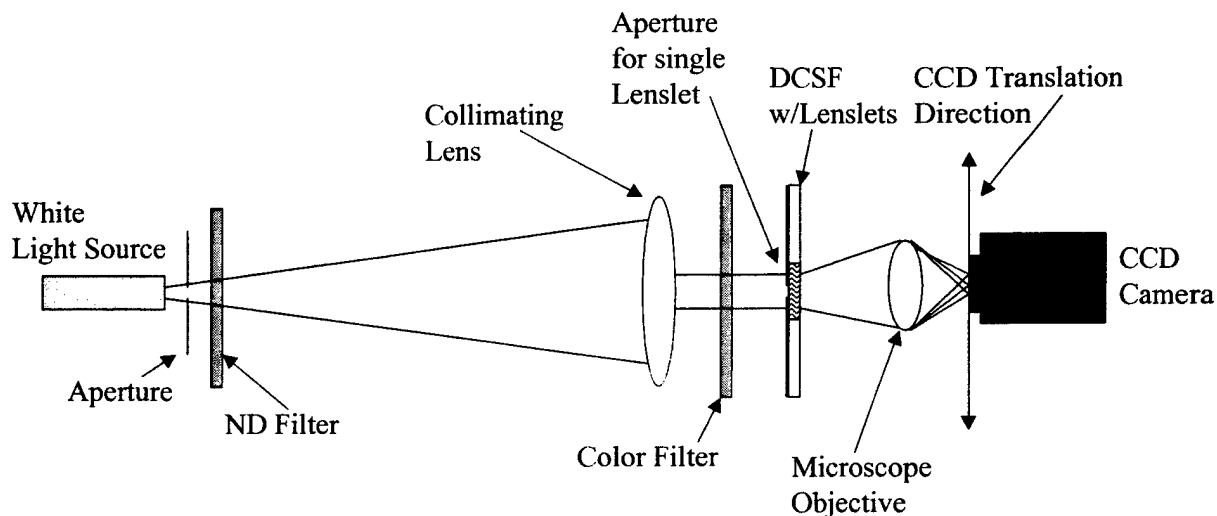
Figure 15(b): Test configuration for the 2X (grating-lens combination) DCSF design

The results of the etching and analysis experiments previous to August 2001 are contained in other sections of this report as follows (in reverse chronological order):

(1) TR Section 3.1.2: "AFMs of Early Binary and Grayscale Gratings" (April, August 1999)
(2) TR Appendix C: "ICS Report 2 - presented at SPIE Photonics West 99" (January 1999)
(3) TR Section 3.1.1, Figure 9: "2X grating-lens in SiO$_2$ only" (March 1998)

This most recent batch of wafers (fabricated in 2001) consisted of 3 in. diameter x 1.1 mm thick Corning 1737 glass coated with approximately 5 μm of a high index material. These wafers were processed using the MEMS Optical proprietary processes for analog grayscale lithography and for etching. Experimental results from five wafers—W4, W17, W19, W20, W21—are shown in Table 1. Results included in Table 1 are: (1) the percent error from the targeted etch depth for each wafer; (2) the broadband color filter used (B390 = blue color filter centered at 390

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nm, G530 = green color filter centered at 530 nm, R60 = red color filter centered at 600 nm); (3) the neutral density (ND) filters used; and (4) the lamp illumination setting used to obtain the data. The wafers were patterned with a 1X (high frequency grating) grating-lens combination. The color separating grating is located on the surface of a focusing element (lens). The experimental configuration used to obtain the image data in Table 1 is shown in Figure 15(a).

Table 1 shows that the resultant patterns have marginal color separation capability. The central order for all filters (as demonstrated by the vertical double-headed arrow in the W19 series), and almost all wafers, appears to be in the same location. That is, the separate colors are not shifted completely to alternate orders. This seems to indicate that the structure of the steps in the grating are somewhat washed out, leaving a pattern that is much like a simple blazed grating. The AFM data seems to indicate this washing out of structure as well. While there is indeed color separation, there is demonstrable cross-talk among red-green-blue (RGB) "subpixels." Compared to the results indicated in Appendix C ("ICS Report 2 - presented at SPIE Photonics West 99"), the multi-layer binary structure (without a focusing element) seems to have the sharpest features and better color separation. Examples can be seen above in the AFM images of the binary multi-layer and grayscale etched in patterns Section 3.1.2: "AFMs of Early Binary and Grayscale Gratings" (April, August 1999).

The previous 2X integrated grating-lens structure also has better color separation capability as well. Because the features are larger, more "wash-out" is tolerated and reasonable performance can still be obtained. Figure 9 shows results for 2X grating-lens combination etched in SiO_2 only (not LCD glass, and not high-index material on LCD glass). This design and material showed good color-separation with reasonably low cross-talk. Silicon dioxide (SiO_2) is a material used in many MEMS Optical etch processes, and MEMS Optical frequently delivers custom parts to customers in SiO_2.

It is interesting to note that wafer W4 (2001) in Table 1 has the highest deviation from the desired etch target, and yet the qualitative color separation capability is comparable to the other four wafers (although only slightly) and there is some ringing structure in the pattern. This is most easily seen in the red-filtered pattern with the ND0.5 filter (W21, W20, and W4). The illumination source had a sizeable amount of red light contained in its spectrum, and thus, yielded the largest illumination pattern with some saturation. The ring structure is possibly due to poor etch quality for both the blaze and the lens. The W4 wafer was located in exactly the same place relative to the other optical elements as the other wafers during the experimental runs.

The AFM scans in Figure 16(a,b,c) and Figure 17(a,b,c) show 3D images of the grating parts at the center of the focusing elements for wafers W21 and W20, respectively (August 2001). These wafers have smoother features than those shown above for the 1X grating only and for the 2X grating-lens combo in Section 3.1.2, "AFMs of Early Binary and Grayscale Gratings" (April, August 1999). As mentioned earlier, this smoothing contributes to these latest, August 2001, gratings behaving more like blazed gratings than color separators.

Table 1: Experimental results with blue, green, and red broad-band filters (August 2001)

W21	W20	W19	W17	W4
Etch depth	Etch depth	Etch depth	Etch depth	Etch depth
+3.1% from target	+1.5% from target	+4.3% from target	+3.6% from target	-8.7% from target
Color filter/ND filter/Illumination	Color filter/ND filter/Illumination	Color filter/ND filter/Illumination	Color filter/ND filter/Illumination	Color filter/ND filter/Illumination
B390/ND0.0/High	B390/ND0.0/High	B390/ND0.0/High	B390/ND0.0/High	B390/ND0.0/High
G530/ND0.0/High	G530/ND0.0/High	G530/ND0.0/High	G530/ND0.0/High	G530/ND0.0/High
R60/ND1.0/Low	R60/ND1.0/Low	R60/ND1.0/Low	R60/ND1.0/Low	R60/ND1.0/Low
R60/ND0.5/Low	R60/ND0.5/Low			R60/ND0.5/Low

Zero order (center-line) for all filtered outputs

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Digital Instruments NanoScope
Scan size   26.40 µm
Scan rate   0.2999 Hz
Number of samples   128
Image Data   Height
Data scale   4.106 um
Engage X Pos
Engage Y Pos

view angle
light angle

x   5.000 µm/div
z   4106.000 nm/div

Figure 16(a): Device W21 – AFM scan showing 3D surface map isomeric view (August 2001)

Section Analysis

L	1.444 µm
RMS	152.15 nm
lc	DC
Ra(lc)	16.313 nm
Rmax	74.369 nm
Rz	48.765 nm
Rz Cnt	4
Radius	3.203 µm
Sigma	26.881 nm

Spectrum

Surface distance	1.441 µm
Horiz distance(L)	2.269 um
Vert distance	2.369 µm
Angle	46.23
Surface distance	1.512 µm
Horiz distance	1.444 µm
Vert distance	422.61 nm
Angle	16.316 °
Spectral period	DC
Spectral freq	0 Hz
Spectral RMS amp	0.655 nm

2090_w20-full.000

Figure 16(b): Device W21 –AFM scan showing profile from 3D surface map

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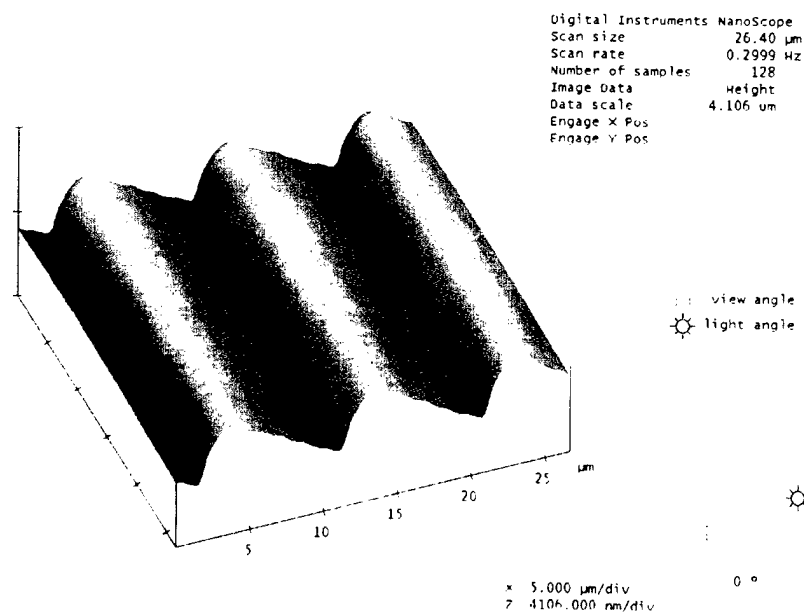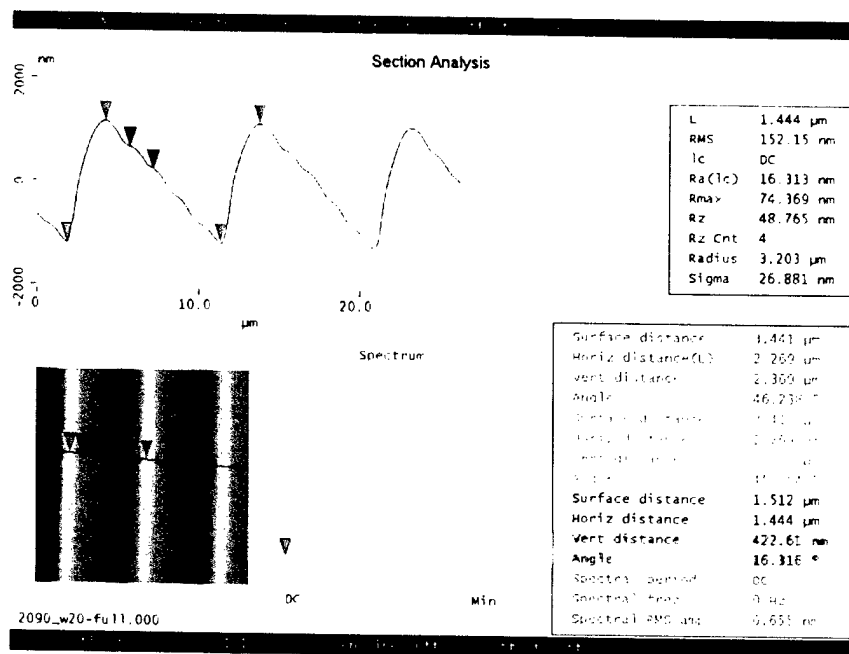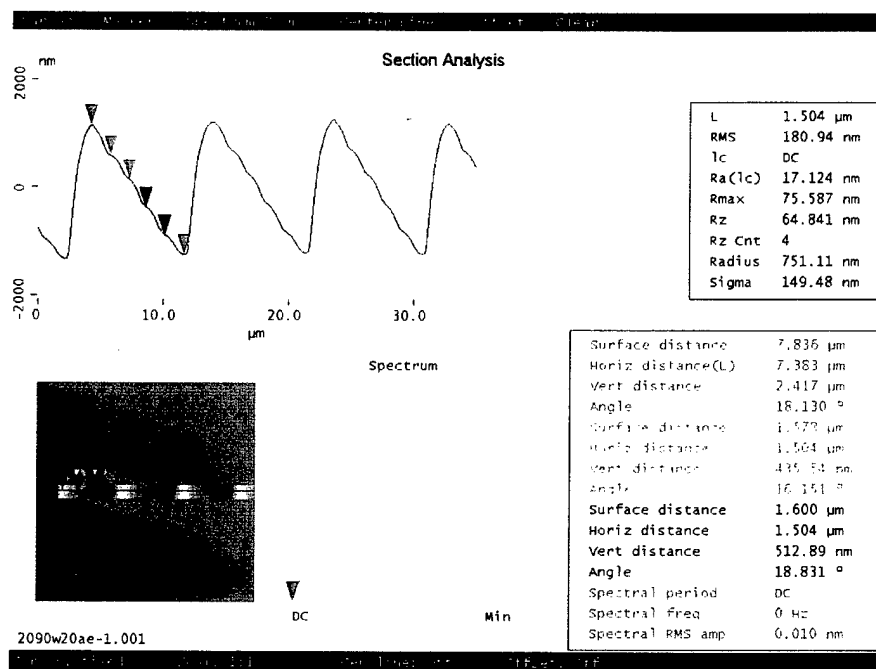Figure 16(c): Device W21 – AFM scan showing profile smaller surface scan
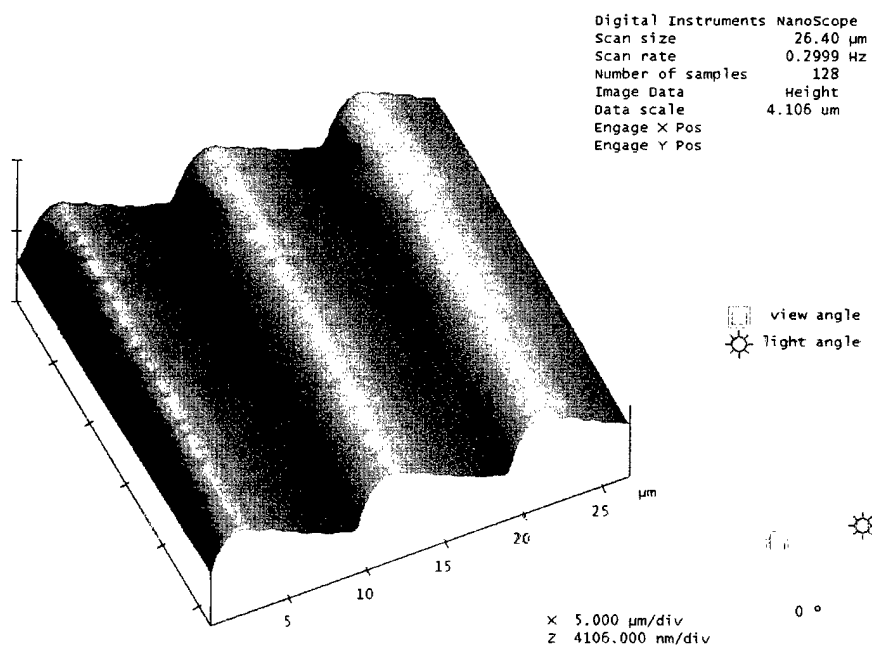
Figure 17(a): Device W20 – AFM scan showing 3D surface map isomeric view (August 2001)
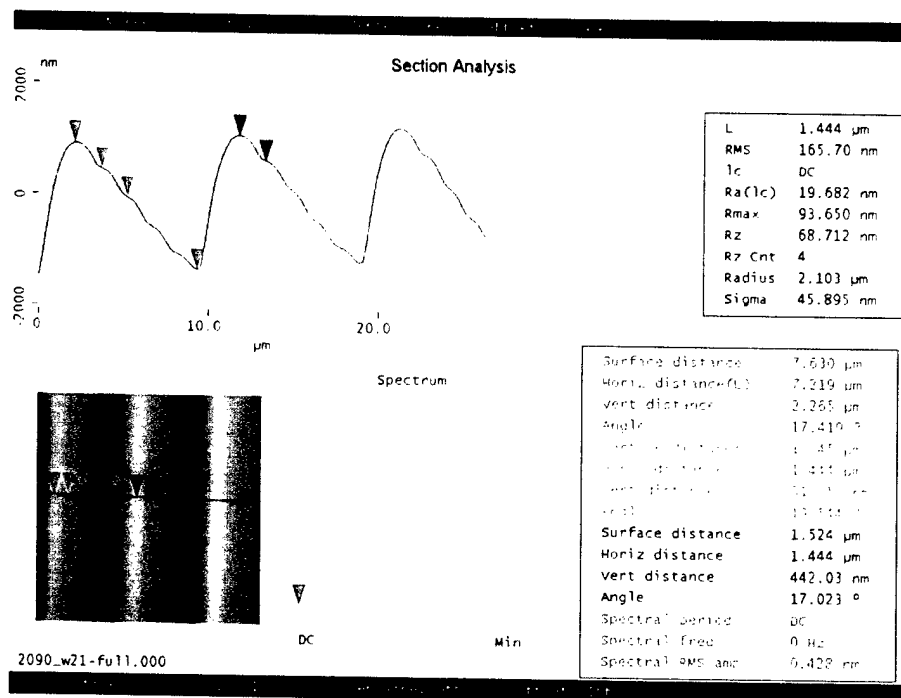
Figure 17(b): Device W20 –AFM scan showing profile from 3D surface map
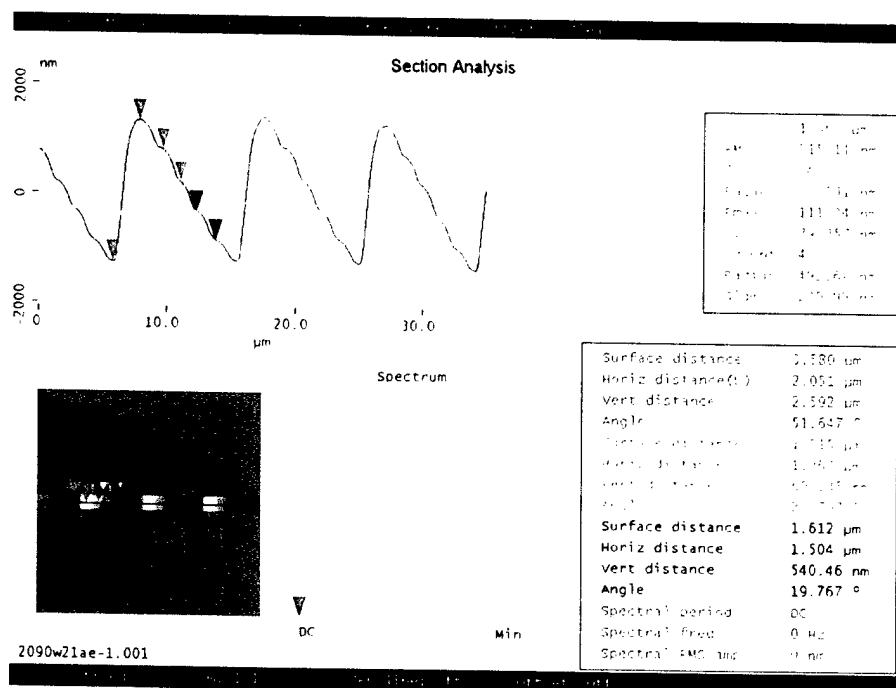
Figure 17(c): Device W20 – AFM scan showing profile smaller surface scan

3.1.4 Compliance Evaluation by BAE Nashua (February 2002). The diffractive optic color separation filter samples provided by MEMS Optical in August 2001 for LCD applications was evaluated by Charles V. Dionne of BAE SYSTEMS North America in Nasuha NH during the period November 2001 to February 15, 2002. Wafers W20 and W21 from Table 1 and Figures 16 and 17 were both evaluated; wafer W20 was found the best and is detailed in this section.

Wafer W20 experimental results obtained by MEMs are documented in Table 1 (column 2) and Figures 17(a,b,c). This filter is a grating-lens array structure etched into a high index material on LCD 1737 glass. Sample grating wafer W20 had the least error, namely +1.5%, from the targeted etch depth. The element was transparent and can be categorized as a self-focusing specialized phase grating designed to separate the RGB color primaries with high efficiency. The optical element was evaluated against a relative color dispersion for an RGB pixel as specified in the statement of work (SoW) given to MEMS Optical. The element also was evaluated according to geometry.

3.1.4.1 BAE Evaluation Experiment Test Setup and Procedure. The test setup and equipment is illustrated in Figure 18. This setup is similar to that used by MEMS Optical (see Figure 15). The notable exception is the use of narrow band filters across the optical band to measure the measurement system's spectral transfer function. The function is used to equalize the system's spectral response in processed data. The filters (Oriel Inc.) have nominal 10 nm spectral resolution defined at full width, half maximum. The filters are also used to measure the relative color dispersion against the SoW and the CSF color diffraction efficiency.

A special precaution was the use of a spatial diffuser at the light source to mitigate any spatial coherence in the light to prevent artifacts related to coherent interference contaminating the desired diffraction results. The broadband light source was a Fibre-Lite (Dolan-Jenner Inc.) that has a fiber bundle coupled output. The individual fiber diameter was 50 μm. Future experiments could incorporate a 20 μm fiber diameter to reduce the spatial coherence even further without affecting system light throughput.

Geometric calibration of the data was provided by the imaging of a calibrated scale placed vertically and then horizontally at the DCSF location in the optical path. This calibration provided the magnification in the imaging optics. Sampling and interpolation was obtained with a high resolution charge-coupled device (CCD) and a 16-bit video digitizer. The CCD was a monochrome camera (Pulnix Inc., Model TM-745E) having a 768(H) x 493(V) pixel format; the pixel size was 11 x 13 μm.

Color data was obtained by post processing of the RGB filtered images with MATLAB software. Colored image data were also obtained by integrating narrow band images into the appropriate colored filter spectral bandwidth. The measured narrow band images were stacked into an image cube and then weighted by the system spectral transfer curve before processing.

The etched surface of the DCSF was pointed toward the CCD, and not toward the light source. This was the orientation used by MEMS Optical in taking their data. In theory, the wafer orientation should not matter if the grating and lenslet array had been etched into the same plane. However, better results were obtained with placement toward the CCD as noted.
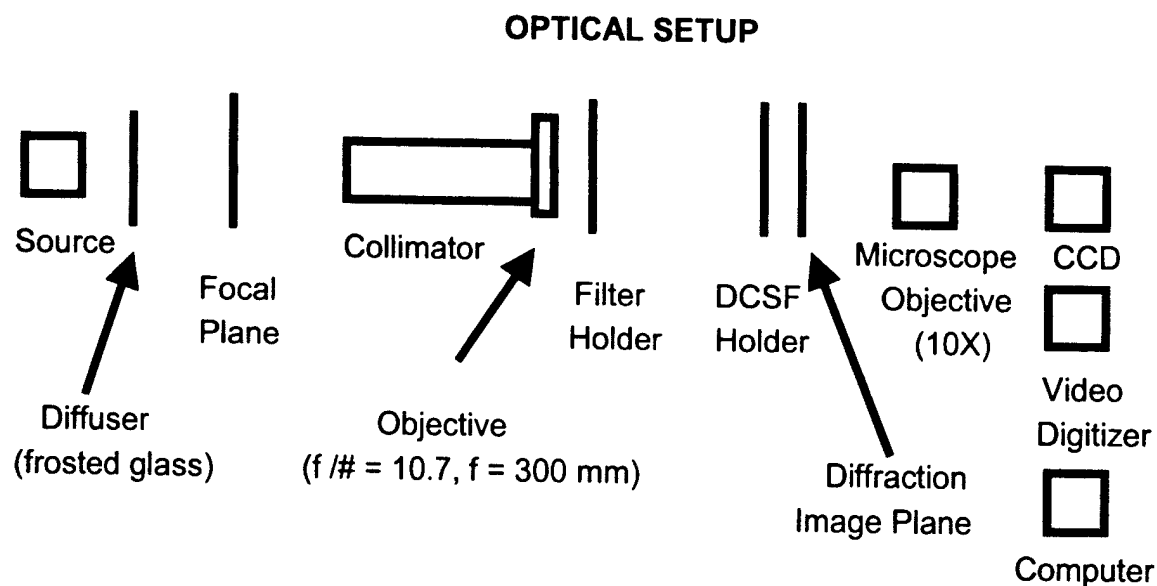
OPTICAL SETUP

Figure 18: Experimental setup used by BAE Nashua for optical evaluation of DCSF samples

3.1.4.2 BAE Evaluation Results. The DCSF colored diffraction results are shown in Figure 19. The red, green, and blue channels were each obtained by integrating the narrow band data within the appropriate color bandwidths.

COLOR SEPARATION RESULTS
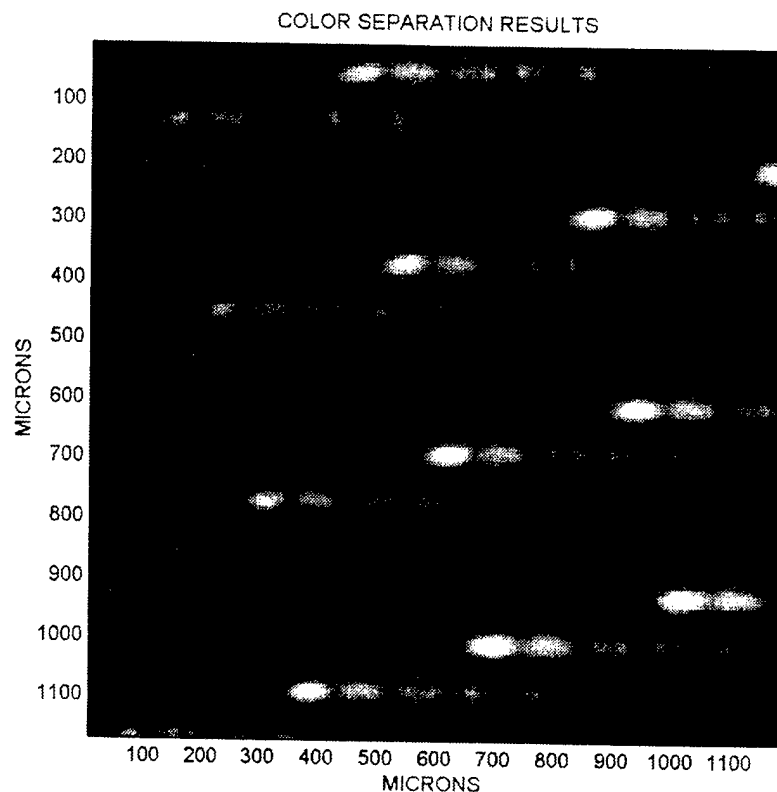
Figure 19: Color separation results obtained by BAE Nashua with MEMS wafer W20

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Examination of Figure 19 shows that a color pattern cell repeats periodically in a black matrix background. The pixel pitch is square and is measured at 330 μm; this measurement is defined to be the distance between the repeating cells. For a given strip in the center of Figure 19 the total distance, center to center, between the red subpixel through to the blue subpixel is 110 μm. These numbers were required in the MEMS design specification. The overall pattern is new and has a tilted nature designed to eliminate undesired diffracted light from the RGB subpixel aperture. It is not clear, however, where the red, green, and blue subpixel apertures are located and how to match the pattern to the LCD pixel formats.[8]

The yellowish streaking seen in the pattern is a periodic, repeatable, undesired artifact in the image. This yellow streaking can be correlated directly to a periodic, repeatable apparent light leakage in the upper left corner of each underlying tilted square lens element cell responsible for imaging each color pattern cell. Figure 20 shows an image of the underlying lenslet array that caused the color diffraction pattern illustrated in Figure 19. The focal length of the lens array averages to 2 mm when measured at the 540 nm wavelength. With an approximate lens diameter of 330 μm, the optical speed (f/#) is 6. The light leakage artifact is apparent in Figure 20.
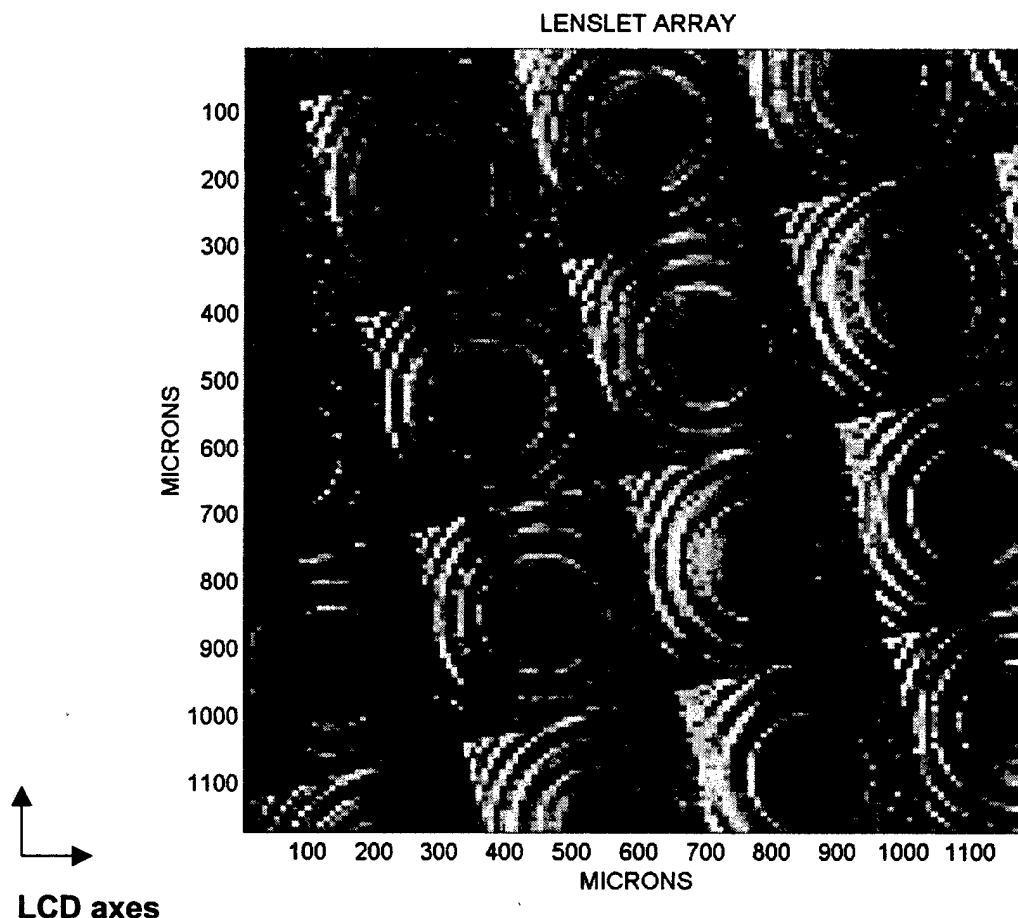
LENSLET ARRAY

Figure 20: Lenslet array image showing tilted lenslet array design for MEMS wafer W20

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[8] Resolution of this issue would require BAE to obtain more documentation from MEMS.

The center of each lens is centered on the faint purple spot seen in each color pattern cell in Figure 19. The source illumination was normal to the DCSF. The light leakage pattern flipped up/down when the DCSF itself is flipped up/down in the same collimated light beam. This test provided evidence that the leakage is caused by something in the DCSF itself. The reason for the blemish is not known, but one possible explanation is a compromised anti-reflection coating in the leakage areas due to the etch process. The lenslet image shown in Figure 20 is with narrow band filtered light at 540 nm. The leakage is evident in all narrow band light throughout the visible band.

In wide band colored illumination, the streaking artifact can be seen in each RGB channel. The wide band RGB color images are shown in Figure 21.

The DCSF results measured against the relative color dispersion metric in the SoW from BAE to MEMS are tabulated in Table 2. Collimated broadband white light illumination with roughly 1° divergence (half angle) was used during the measurement. The red aperture was assumed centered on the location of the most intense red spot. The same assumption was used for the green and blue aperture locations.

RED CHANNEL   GREEN CHANNEL   BLUE CHANNEL
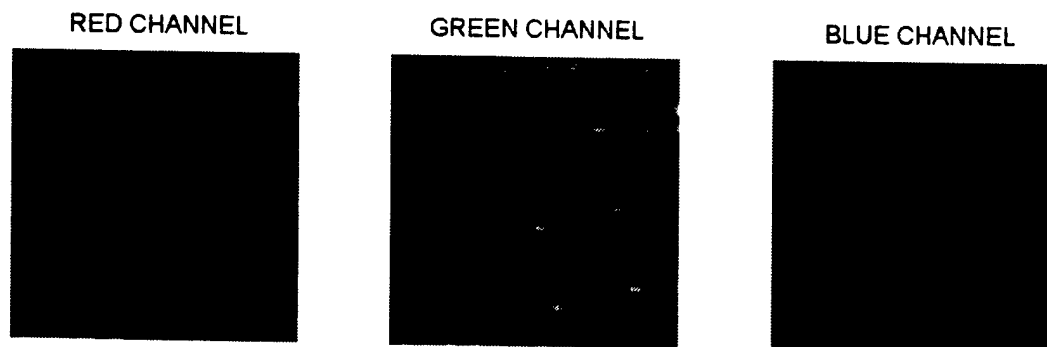
Figure 21: RGB images obtained by BAE Nashua for MEMS wafer W20

Table 2: Comparison of relative energy by band in the BAE specification (BAE-MEMS SoW) to measurements made by BAE Nashua on MEMS wafer W20

Location	Wavelength (nm)	RELATIVE ENERGY Specification (%)	Measurement (%)	Pass/Fail
RED APERTURE	400 - 580	< 2	36	Fail
	580 - 600	< 15	10	Fail
	600 - 730	> 95	53	Fail
GREEN APERTURE	400 - 480	< 2	24	Fail
	480 - 500	< 15	7	Fail
	500 - 555	> 95	32	Fail
	555 - 580	< 15	16	Fail
	580 - 730	< 2	21	Fail
BLUE APERTURE	400 - 480	> 95	50	Fail
	480 - 500	< 15	8	Pass
	500 - 730	< 2	42	Fail
BLACK MATRIX	400 - 480	< 5	28	Fail
	480 - 500	> 65	3	Fail
	500 - 555	< 5	22	Fail
	555 - 600	> 65	24	Fail
	600 - 730	< 5	24	Fail

The DCSF data in Table 2 show that wafer W20 passed just 1 of 16 color band specifications given to MEMS Optical by BAE Nashua in 1998. Although there is visual color separation, there is also spectral cross talk between the RGB pixels. This crosstalk can be seen in Figure 22, a plot of the normalized irradiance distribution through the horizontal center line of the red, green, and blue pixels of a given color strip. Figure 22(a) shows the entire field of view (entire strip). Figure 22(b) shows only the central red, green, and blue subpixel triplet. The colors used in the plot matches the red, green, and blue pixels being plotted in a given horizontal strip.

SCAN OF THE ENTIRE COLOR STRIP

SCAN OF THE CENTRAL RGB SPOTS

(a)

(b)
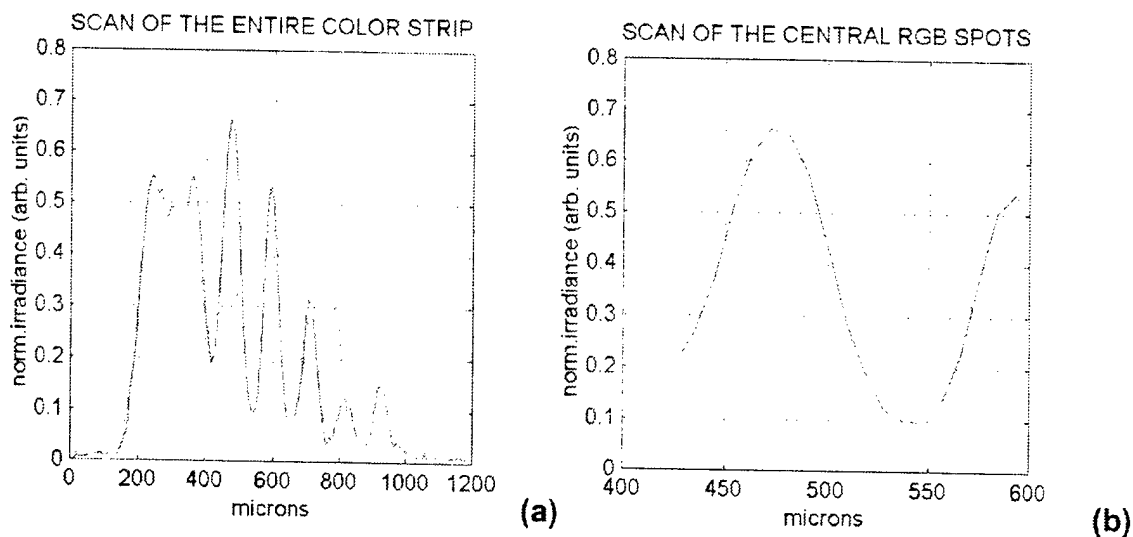
Figure 22. Crosstalk illustration for wafer W20 via plots of the normalized irradiance distribution through the horizontal center line of the red, green, and blue pixels of a given color strip: (a) scan of the entire color strip; (b) scan of the central RGB spots

The scan illustrated in Figure 22(b) of the central RGB triplet shows spatial separation, but each color component has mixtures of the other color components. The spectral distribution in the black matrix is near flat, suggesting a uniform, low intensity light scatter of the source into the matrix.

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3.2 Inorganic Light Emitting Diode (LED) Backlight and Lens (August 1999)

As part of their 18 August 1999 report MEMS proposed an alternative approach for the HEAMLCD program based inorganic light emitting diodes (LEDs) as illustrated in Figure 23. Two variants of this approach were described, one based on the use of red, green, and blue (RGB) colored LEDs; another, on white LEDs.

The RGB approach has the advantage that the spectra are narrow and would minimize cross-talk.
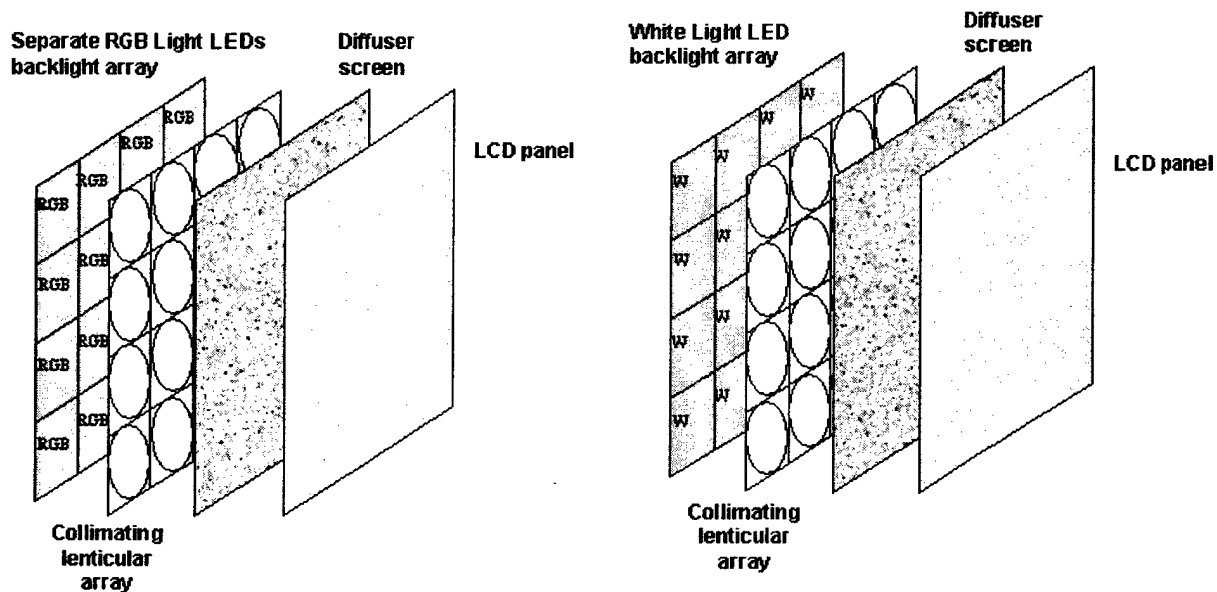
Figure 23: LED RGB/white backlight and collimating lens designs (August 1999)

3.3 Review of Overall Program by BAE Edinburgh (October 2002)

A review of the overall HEAMLD program was conducted from April to October 2002 by David Craig of the BAE Avionics Systems Division in Edinburgh, Scotland, U.K. The results and recommendations were documented in a report dated October 7, 2002. The purpose of the review was to assess what the project has achieved during its first 6 years, what its prospects were for success, and what its future direction should be. The a discussion of the results is presented in this section and Mr. Craig's recommendations, in Section 5.2.

The use of display expertise from BAE SYSTEMS in Edinburgh UK made up for the loss of key personnel in Nashua NH just before the acquisition by BAE of Sanders Avionics from Lockheed Martin. Displays activity at Lockheed Sanders had been discontinued just prior to the time it became a part of BAE SYSTEMS in November 2000. Therefore, this review was undertaken by the Avionic Systems division of BAE SYSTEMS, which makes avionic displays in Edinburgh, Scotland, U.K. The delay in starting this study (from mid-2001 to early 2002) by BAE Edinburgh UK was occasioned by international business issues, namely (a) the obtention of an export licence agreement from the DoD and DoS (accomplished during the period June to December 2001) followed by (b) the establishment of a Technology Assistance Agreement (TAA) from BAE North America to BAE United Kingdom to permit passing of all prior contract data files. The TAA was accomplished during the period January to March 2002. Data files were then provided to Mr. Craig during a programmatic contract business meeting in Orlando FL attended by BAE Nashua (Mitch Burte), BAE Edinburgh (David Craig), and AFRL (Dr. Hopper, Maj Desjardins) on April 1, 2002.

Mr. Craig based his review on previous publications and discussions with personnel at BAE Nashua and MEMS Optical. The four previous publications on the HEAMLCD project in 1996, 1997, 1998, and 1999 provided the project background and progress through January 1999:

Rich Hicks, "A new architecture for high efficiency AMLCD's," in *Cockpit Displays III*, Darrel G. Hopper, Editor, Proceedings of SPIE Vol. 2734, pp. 46-56 (1996).

Richmond F. Hicks, Wes Halstead and Thomas Gunn "Diffractive color separation for high efficiency LCD's," in *Cockpit Displays IV: Flat Panel Displays for Defense Applications*, Darrel G. Hopper, Editor, Proceedings of SPIE Vol. 3057, pp. 200-211 (1997).

Thomas V. Gunn and Wes Halstead, "Diffractive color separation fabrication," in *Cockpit Displays V: Displays for Defense Applications*, Darrel G. Hopper, Editor, Proceedings of SPIE Vol. 3363, pp.198–208 (1998).

Peter S. Erbach, Gregg T. Borek, David R. Brown, and Tom Gunn, "Diffractive color separation filter for high efficiency LCD panels," in *Flat Panel Display Technology and Display Metrology*, Bruce Gnade and Edward F. Kelley, Editors, Proceedings of SPIE Vol. 3636, pp. 48-59 (1999).

Mr. Craig held discussions by telephone and e-mail with MEMs Optical personnel, and made a one-day visit to the BAE Nashua NH facility to interview staff there who had worked on the project, including Tom Gunn. This specific input has been examined by Mr. Craig in the light of his existing expert knowledge of aircraft display requirements, and the detailed engineering process of designing 'conventional' AMLCD avionic displays.

3.3.1 Assessment of Original Approach. The origins of the HEAMLCD project lie in the observation that 95% of the light generated by the backlight is absorbed in the AMLCD. This inefficiency is particularly significant for cockpit displays because they need to be bright to be sunlight readable. The project proposes a method of splitting the white light from the backlight into red, green, and blue components and directing these through the RGB subpixels of the LCD. This approach is projected to improve the normal light utilization efficiency (~5%) by 3 or more times (to ~15% or more).

The architecture described in the first paper (Hicks 1996) has three key elements: (a) collimated backlight, (b) a diffractive color separator filter, and (c) a diffusing screen. All three elements must work in order for the overall DCS approach to succeed. It was decided early in the project that developing the DCS filter was the hardest part, and most of the efforts has gone in this direction. This approach was not unreasonable, given limited resources, but it must not be forgotten that the other elements (collimated backlight and diffusing screen) are also necessary. Hicks foresaw two main performance advantages: efficiency and contrast/viewing angle.

3.3.1.1 Efficiency. The overall 'conventional' AMLCD lighting efficiency presented in the 1996 paper (Hick, 1996, Figure 1) is actually under-estimated. In particular, Hicks suggests that a divergence reduction filter will reduce the display luminance by 10%, whereas in fact the main function of this filter is to *increase* the display luminance in the viewing zone by around 50%. Also, the ACA transmission is taken by Hicks to be 2.6%, but current AMLCDs available in 2002 (better than those available in 1996) achieve ACA transmission of around 5%. Thus, the conventional efficiency should be at least 3.5 lm/W with year 2002 components and a correct analysis, rather than the 1.2 lm/W found by Hicks in his analysis with year 1996 components.

The new, DCS AMLCD design proposed at the beginning of this HEAMLCD effort is illustrated in Figure 24 (after Hicks, 1996, Figure 8), which shows the predicted improvement in luminous efficiency. In this figure Hicks includes a 'Transflective Polariser.' However, the use of the term 'transflective polarizer' in this paper appears to be an error because this term is generally used to describe a conventional polarizer with a leaky reflective layer placed behind low-information-content character-only LCDs (such as used in cheap calculators). It is not clear what Hicks intended, but later papers dropped this aspect, so it seems likely that its inclusion was an error. Correcting this error modestly reduces the predicted efficiency for the new, DCS AMLCD design arrangement from 24 to about 20 lm/W, which would still be a 6X improvement compared to the 'conventional' AMLCD.

3.3.1.2 Contrast and Viewing Angle. Dark ambient contrast in the 1996 Hicks paper was claimed to be modestly improved on-axis, and greatly improved off-axis by use of the DCS approach. Since 1996, mainstream AMLCD viewing angles have been increased by other methods, so that in this respect the proposed DCS architecture no longer gives much advantage.

Bright ambient contrast in the 1996 Hicks paper is seen as a potential problem, to be overcome with a new type of 'graded index scattering film'. This term is understood to refer to the polymer type of diffuser made in the UK by Microsharp.[9]

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[9] Reference: www.microsharp.co.uk

85%   38 lm/w   85%   90%   85%   99%

2.1 w   80   68   62   52.5   52

Efficient
Power   Transflective   TFT, LC,
Supply   Polarizer   And Polarizer

Waveguiding   Diffractive
Collimated   Color   Graded Index
Backlight   Separator   Diffuser

Efficiency of a 8" by 6" display at 350 fL and a 120 by 40
viewing cone. System efficacy stacks up to > 24 lm/w
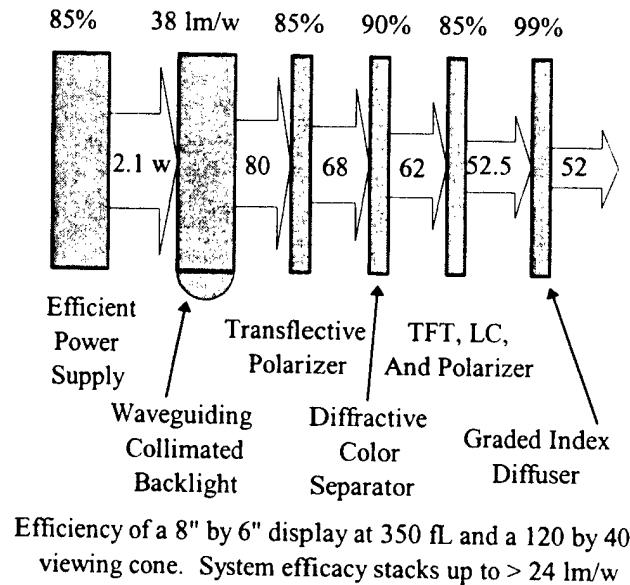
Figure 24: New DCS AMLCD design proposed at the beginning of the HEAMLCD program
(after Hicks, 1996, Figure 8).

Unfortunately, the reflectance of this film is considerably higher than seems to have been assumed in 1996 by Hicks: the most significant difference between the Microsharp product and conventional diffusing screens is not a dramatically reduced reflectance, but that the scattering angles horizontally and vertically can be made asymmetrical. A sample of 'Microsharp I' with a 45° viewing cone has a measured diffuse reflectance of 8.3%. This reflectance has a large and probably fatal effect on the high ambient contrast of the system. Taking the typical reflectance to be 8% rather than the 0.1% assumed by Hicks (1996), the contrast of a 200 fL display in 10,000 fc of sunlight is $C = (S+N)/N = (200+800)/800 = 1.25$, which is unacceptable. A helpful feature of this diffuser is that it retains the polarization of the light which passes through; in this application, the diffuser can be placed between the LCD glass and the front polarizer. This arrangement is specifically excluded in the 1996 Hicks paper because of the risk of affecting the polarization purity (and hence the dark ambient contrast), but it would help to reduce the apparent reflectivity. This is a serious problem, and little work on this aspect of the design has been done. The effect of light from the LCD being backscattered from the diffuser is also not considered by Hicks (1996), but can be expected to reduce dark ambient contrast.

3.3.1.3 Commercial Aspects. The DCS AMLCD approach requires that the color separator will be designed to be compatible with a monochrome AMLCD cell. At the outset of the HEAMLCD project, it was assumed that these monochrome AMLCD cells would be obtained from US-based display manufacturers who would be interested in supporting specialized display types. However, since 1996 all specialized AMLCD manufacture has ceased in the US and Canada, and monochrome AMLCDs have become almost impossible to obtain. Manufacture is technically straightforward, but without a large market it will be difficult to get high volume sources—which exist only in Japan, Korea, and Taiwan—to co-operate. Even if this Asian cooperation were secured, the need for 'special' LCDs would inevitably limit the range of sizes and resolutions available, undermining the attractiveness of the product.

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If large power savings were obtained, then the laptop market might seem an attractive target. Such mass market adoption would solve the problem of LCD supply; but the collimated backlight is likely to be considerably more bulky than what is currently used, and application to laptops therefore seems unlikely. It is also arguable that if the market is laptops, the development should be driven by a laptop manufacturer, rather than BAE SYSTEMS.

3.3.1.4 Technical Aspects. Little has been done about the diffusing screen needed by the DCS AMLCD approach. Some effort has been expended on the backlight. Most of the effort has focused on the DCS filter fabrication.

The collimated backlight design originally proposed (Hicks, 1996) used aperture fluorescent lamps and an array of non-imaging plastic 'light concentrators.' This diffusing screen concept was acknowledged in 1996 to be clumsy, and design details are no longer available. By 1999 it was determined that a better approach would use inorganic LEDs, as noted by MEMS Optical in their 18 August 1999 report to BAE SYSTEMS (see Section 3.2 and Figure 23 of this report; see also Brown et al.[10] It seems probable that a collimated backlight can be made, but the size, efficiency, and cost are still uncertain. These parameters will all be considerably worse than in a conventional backlight, and it is not obvious that the DCS efficiency improvement would more than offset these disadvantages.

The DCS comprises an array of 1 mm focal length lenses, and a diffraction grating. The lenses create an array of white light spots and the diffraction grating splits each white spot into 3 RGB spots that pass through the open areas of the RGB subpixels of the AMLCD. A number of attempts have been made to realize the DCS filter. This emphasis within the overall HEAMLCD project is reflected in the title of the 1998 paper by Gunn and Halstead, "Diffractive color separation fabrication," and the 1999 paper by Erbach et al., "Diffractive color separation filter for high efficiency LCD panels." It is apparent that the proposed design using 1 mm focal length lenses has multiple deficiencies. The 1 mm design was probably chosen to allow a standard commercial AMLCD to be used with the idea being to ultimately manufacture AMLCD cells using the DCS filter substrate as one side of the cell. This concept also forced the co-location of both diffraction grating and lens array on the same side of the substrate. This co-location in turn forced the designers at MEMS Optical to use a new high index material, and to attempt to etch deeper and sharper features than previously. It is now apparent that a 1 mm design is not feasible.

An alternative approach is to separate the DCS from the AMLCD cell, which would allow the focal length to be relaxed to 2 mm and allow the lens array and diffraction grating to be on opposite sides of the substrate. Thus, each surface does less work, and shallower features could be used making optical element fabrication easier. A satisfactory 2-in. sample of such a DCS has been made, and scaling this up to say 6 x 8 in. size seems quite feasible. The estimated manufacturing cost of this alternative approach is about $1K, which is within the bounds of acceptability.

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[10] Daniel M. Brown et al., "LED backlight: design, fabrication, and testing" *Light-Emitting Diodes: Research, Manufacturing, and Applications IV* 2000).

3.3.1.5 Discussion of Original Approach.

The key questions to be answered regarding the original, DCS approach to the HEAMLCD project during the 2002 BAE Edinburgh review were:

> Are the performance advantages useful?
> Are they feasible?
> Is the scheme cost effective?

The performance advantage desired is a reduction in the power consumption of a display. For example, a conventional avionics AMLCD of 6 x 8 in. size putting out 200 fL would typically draw 75W from the aircraft power supply, as detailed in Table 3.

Table 3: Typical power budget for conventional avionics AMLCD

Typical power budget for 200fL 6x8 display	
Module	**Power consumption (W)**
Video electronics	18
Fan	5
Lamps and Driver	39
Relay Main Power	3
LVPS Losses	10
Total	75

A typical fast jet cockpit would use two displays; a helicopter or transport, four displays. In the fast jet this power is modest compared with other needs, although heat build up in the cockpit, particularly behind the instrument panel, can be a problem. In a civil transport aircraft, the power is of little consequence, but in a helicopter it is significant. The backlight accounts for about 60% of the power drawn by the display. Reducing the backlight power would have various other beneficial knock-on effects in the display design. Less backlight power means less demand on the internal low voltage power supply (LVPS), which stabilizes the aircraft supply, which results in mass and cost savings. As power is reduced there is less need for an internal fan to cool the display, which brings further advantages either in reliability (if a cheap fan is used) or in cost (if a quality fan is chosen).

It is concluded that the performance advantages of the original DCS approach *are useful*.

With modifications a DCSF element is assessed to be still be feasible, and the collimated backlight is assessed to be achievable. But the low reflectance diffuser screen appears not feasible. Since the DCS scheme requires all three components to operate, the overall conclusion is that the original DCS approach is *not feasible*.

The projected additional recurring costs of collimator, DCS filter, and diffuser need to be offset against savings identified above. On balance, there seems little doubt that the overall cost of a display would increase significantly, but perhaps not more than would be justified by the increased performance. The biggest uncertainty here is the cost (and difficulty) of sourcing a

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monochrome AMLCD. The non-recurring engineering (NRE) development costs for a cockpit display incorporating these features would be many millions of dollars, and there will be substantial risk even if the current DCS experimental work were to be brought to a successful conclusion. The DCS design would not be commercially viable unless a substantial number (millions of units) were needed to drive down the recurring engineering (RE) expenses of product improvements. Some of the NRE could be amortized over a family of displays, but the NRE would still be a difficulty. The final answer here is less clear cut, but the expert opinion of BAE Edinburgh (Mr. Craig) is that the package (NRE + RE + risk) balanced against the likely premium the market would accept for the improved performance means that such a development would *not be profitable* over the short or medium term (3-8 years).

3.3.2 Alternative Applications of the DCS Components. A collimated backlight has a potential application to improving the night performance of a cockpit display. A variant of collimation might be used to tightly control the cone of light emitted by the display, and in the night cockpit this would be a welcome way of reducing the effect of canopy reflections. Unfortunately, design details have not come to hand. This application would be outside the scope of the HEAMLCD contract, which is directed to improving efficiency.

The DCS, at least in its 2 mm focal length variant, has been shown to work remarkably well. It is, however, difficult to see how to use this component outside the architecture of the project. One possible avenue would be in LCD projection displays, where conventional color splitting typically takes up a lot of space. The LCD pixels in this application are smaller, but perhaps within the bounds of the technology. Another possibility is to re-use only the microlens array, but the diffractive techniques used by MEMS Optical may not be the best way of achieving this.

3.3.3 Alternative Approaches to Improving AMLCD Efficiency. Three promising avenues (other than DCS) toward the goal of improving cockpit display efficiency are presented in this section: reflective color separation, reflection reduction, and increased backlight efficiency.

3.3.3.1 Reflective Color Separation. This idea of reflective color separation (RCS) was briefly considered by Hicks (1996). The concept is illustrated in Figure 25. Color separation is done with lossless reflective filters: the unwanted light from each subpixel is reflected back to the backlight where it is hopefully recycled. Hicks rejects this approach on three grounds: (1) the reflected light passes through the rear polarizer before being recycled; (2) the cost of the patterned dichroic filter; (3) the high reflectivity of the color separator as seen by the viewer. It seems worth revisiting this RCS idea given that the favored DCS approach has proved impracticable. Hicks' points 1 and 3 can be tackled by placing the color filter behind the rear polarizer, and using an array of microlenses similar to one component of the DCS. Point 2, the cost, will be dramatically reduced by the recent successful application of patterned dichroics to Texas Instruments digital light processing (DLP) projectors, and the consequent volume production of similar items, described by Dewald et al.[11] In this case, the patterned dichroic filter improves light efficiency of a projector by recycling light in a manner similar to the one proposed here for a direct view display.

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[11] D. Scott Dewald et al., "Sequential Color Recapture and Dynamic filtering: a Method of Scrolling Color," *SID Digest 2001,* paper 40.2 (2001).
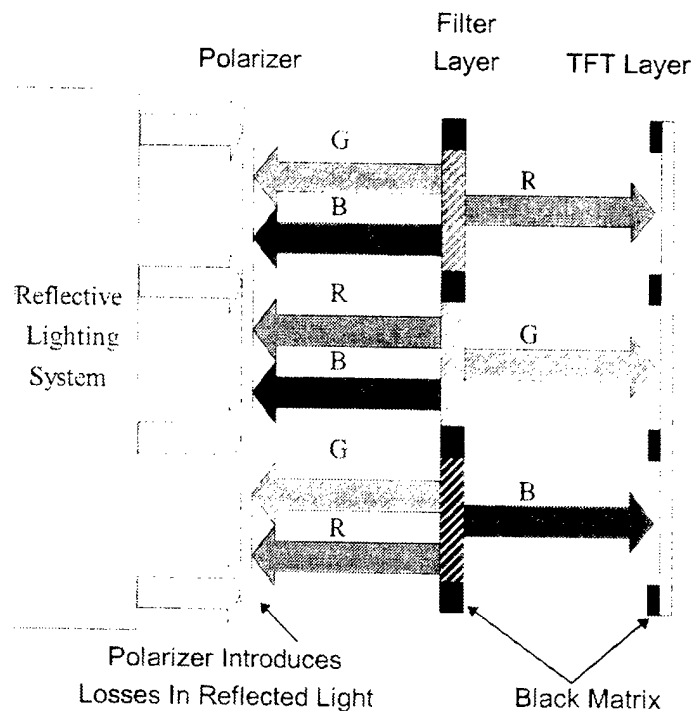
Figure 25: Reflective color separation concept (after Hicks,1996, Figure 6).

The implementation suggested by Mr. Craig is shown in Figure 26. A conventional uncollimated backlight is enclosed with a dichroic filter, patterned into RGB stripes as on most color LCDs. This dichroic filter reflects the unwanted light, allowing it to be recycled and improve the backlight luminance (its efficiency) by some 50%. The exact gain is difficult to calculate, as it is critically dependant on the diffuse reflectivity of the backlight, but a similar gain is experienced using brightness enhancing film (BEF), which relies on recycling light traveling in unwanted directions. The microlens array focuses these colored stripes onto the LCD subpixels of the corresponding color. Note that the conventional absorption color filters are still present, so standard AMLCDs can be used.

Two difficulties are apparent: the dichroics are angle sensitive and stray high angle light of inappropriate color will be present. Hopefully, the retained absorption filters will clean up this stray light. Light is not emitted towards the viewer at all angles; this situation may be an advantage in a cockpit situation, but it is important that the relative intensity of the colors does not change with viewing angle. Some form of diffusion may still be necessary at the output side.

Backlight Filters on glass, Microlens   Rear LCD cell substrate array, Polarizer

microlenses
t= 0.8mm
dia = 0.9mm
F#1
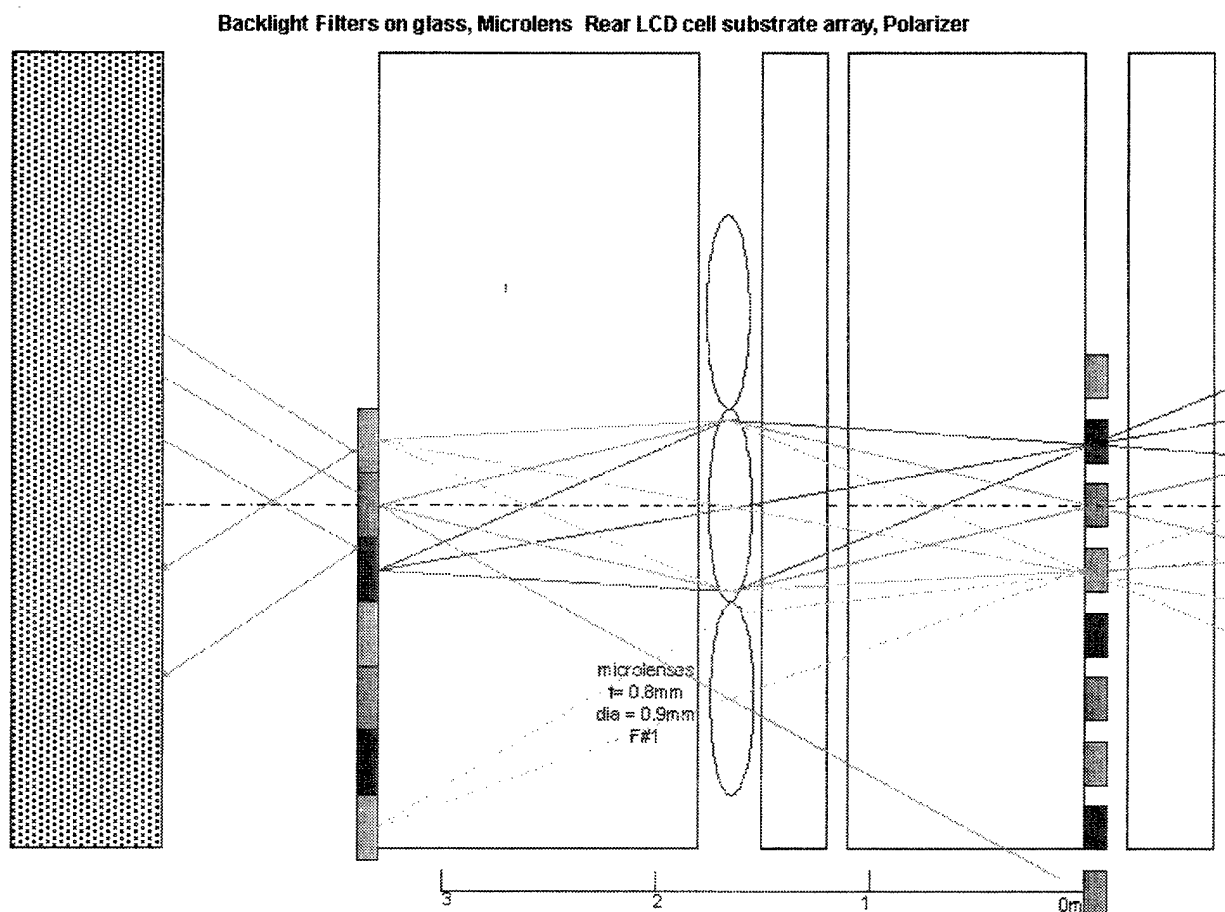
Figure 26: Reflective color separation implementation suggested by Craig, 2002.

3.3.3.2 Reflection Reduction. Although AMLCDs have an intrinsically low reflectance, it is not zero, and various techniques have been used to reduce the reflectivity and increase the display contrast. Effective contrast enhancement (CE) reduces the required display luminance, resulting in a more efficient display. 'Disruptive' technology developments are not anticipated from research on reflection reduction, but it is apparent that display designers do not have access to a rigorous, unbiased assessment of the various techniques.

Mr. Craig proposed to provide an unbiased assessment of the various reflection reduction techniques by working with a UK interest group called the Displays Viewability Consortium (DVC) as described in Table 4. This consortium of non-competitive partners from industry and academia pursues a joint interest in measuring, specifying and designing sunlight readable displays. This consortium leverages the resources and skills of each partner to provide a more comprehensive suite of CE techniques, a more rigorous set of measurements, and a psychologically valid visual assessment of the effectiveness of each technique.

Table 4: Displays Viewability Consortium (UK) for Sunlight Readable Displays

MEMBER	ROLE
NCR	Manufacturer of hole-in the wall cash machines
University of Abertay	'The Epicentre,' Expertise in Human Factors of displays and Display Metrology. DVC Coordinators.
BAE SYSTEMS Avionic Systems	Manufacturer of aircraft displays
Paisley University	Thin Film Centre—a recent initiative with state-of-the-art facilities for coating a wide variety of surfaces. Complex and unusual coatings are feasible given the expertise and non-production nature of the centre.
BAE SYSTEMS Air Systems	Originators of the PJND method. Responsible for determining the specification of a display for a particular application. Coordinate the utilization of the specialist Ambient Lighting Facility at Warton UK
Global Display Solutions	Expertise in display design and integration. Supplier to many major companies (including Raymarine and NCR) that require bespoke (custom) solutions which often involves total re-designs of the display assembly (backlight, enhancement films, polarizers, screen coatings, etc.)
Raymarine	Production of displays for use in leisure craft for navigation, radar, etc.. The displays are often content rich, sealed , and mounted on deck so that very little shielding from glare is possible

The proposed plan is to construct about six identical AMLCDs and backlights and apply to each a different combination of state-of-the-art reflection-reducing treatments. The reflectance and luminance of the displays are to be measured using the most advanced equipment available, and the results analyzed and weighted using the methods of MIL-STD-85762 and the BAE SYSTEMS PJND method. Performance metrics are to include the following: luminance, contrast, PJNDs, solar loading, environmental robustness, and cost. It is expected that other aspects like haze or resolution will also need to be considered, and perhaps the effect of fingerprints on future touch screens. A generic filtering scheme is shown in Figure 27. The following seven (7) filtering techniques need to be compared:

- Grey Filter/ triple peak filter

The front filter glass has a high transmission in the RGB peaks of the display emitted spectrum, and is much lower elsewhere. This filter is claimed to suppress sunlight more effectively than a neutral grey filter. It may also be expected to affect (perhaps improve) color variation with viewing angle.
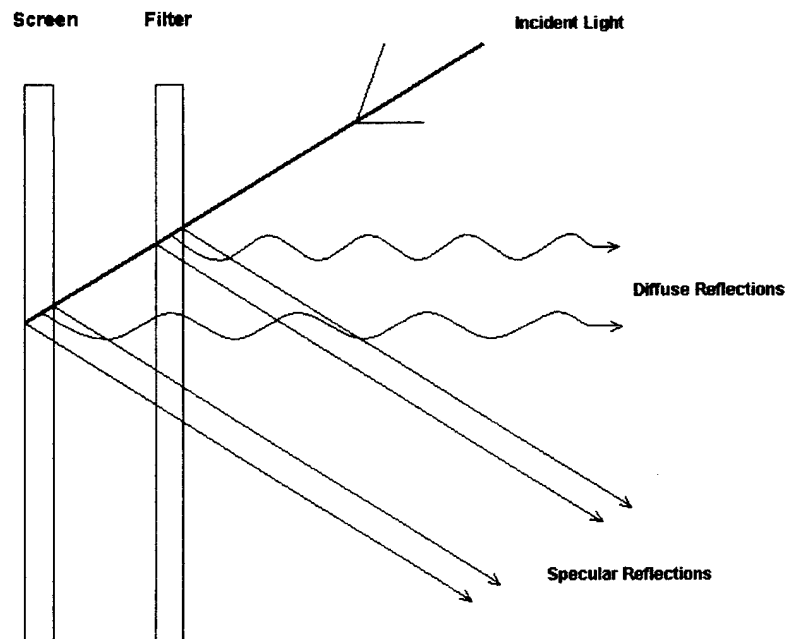
Figure 27: Generic filtering scheme.

- Circularly polarizing filter

The circularly polarizing (CP) filter is a widely used technique that is particularly effective at suppressing specular reflections from the LCD, but at the price of sacrificing a lot of display light. The diffuse reflectivity of the CP filter itself is not generally considered.

- Microlouvres

Microlouvres are often used to reduce the effect of sideways scattered light at night, but have had little attention in the avionics world as CE filters. However, where sunlight is incident at a high angle, microlouvres can be very effective. Again, diffuse reflectivity of the filter itself is an issue, as is the effect on display resolution. Since the results are geometry dependant, the study would consider typical cockpit layouts.

- Polarizer relocation

The polarizer relocation technique is used by BAE SYSTEMS, where the front polarizer is fitted not to the AMLCD but in the separate front instrument glass. Here it acts as a CE filter as well as the analyzer for the AMLCD.

- Inefficient polarizer

Commercial LCDs are normally fitted with polarizers with the highest transmission possible, which is around 42%. All CE filtering techniques generally look to sacrifice some transmission in exchange for better contrast. An elegant way of doing the same thing would be to use a *low*

transmission polarizer (i.e. an inefficient one). Some of the more robust polarizers have transmissions of 25%, yielding an environmental benefit as well as the CE improvement.

- Filter bonded/separated

It is generally acknowledged that bonding the front filter to the LCD with an index matching material is an optically superior method of CE. A disadvantage is the difficulty and cost of the process, and possibly solar loading effects. Thus, each applicable method needs to be studied in both bonded or separated configurations.

- Anti-reflective coatings

All anti-reflective (A/R) coatings are not equal. Different manufacturer's coatings, to apparently similar specifications, perform differently. There is a need to provide an independent comparison, which here might look specifically at the effects on cockpit displays. A particular interest is the ease of cleaning, and the effect of fingerprints on real installed displays. There is a suspicion that contaminated A/R coatings may in some circumstance make the displays in the field worse, not better.

Another novel aspect is the emergence of A/R coatings on antiglare (AG) glass. These AG finishes are generally used in picture framing or on laptops, and are generally seen as a cheap way of suppressing specular reflections. Adding an A/R coating on top of the rough AG finish is a new innovation, and there is a need to study its effectiveness in cockpit situations. It seems likely that in direct sunlight it will not perform well, but in situations like air transports it may give a performance advantage. A rough finish *may* also benefit a touch screen, by being more resistant to fingerprints.

It will first be necessary to ensure that the A/R coating has been optimized for the A/G application, as the rough surface will affect both the deposition of the films and the effective angles of incidence at the surface. Further, it will be necessary to look at the human factors aspect of specular reflections. Current metrics look at the photometrics, regarding all reflections as contributing background glare. But specular reflections contain an image, which is distracting, particularly if it moves. It is precisely to avoid this that A/G finishes are used, but cockpit standards ignore this effect. The result has been pilot complaints that they can see their face, or a hand operating buttons, even though the measured display reflectivities are very low.

3.3.3.3 Increasing Backlight Efficiency. Great efforts have gone into optimizing the efficiency of the backlight in laptop computers, and although some of this can be applied to cockpit displays, the requirements here are very different. The displays need to be brighter, they need to be dimmable, and they need to work over a wide temperature range. Hence although many cockpit displays use AMLCDs which are similar to commercial components, all manufacturers use special–to-type backlights. All cockpit AMLCDs in the field use either hot or cold cathode lamps (CCL), and the application of LEDs in development was announced in April 2002 at SPIE Aerosense 2002—along with the surprising claim that the LED approach was more efficient. This purpose of this work package is similar to the previous one, to provide a fair comparison between the technologies in terms of their overall efficiency.

Whichever technique is used, it is necessary to consider the complete display when making a fair comparison. For example, aircraft power needs to be conditioned and stabilized, and fluorescent lamps need to be heated when cold. Fans, which themselves consume power, may be used to control the lamp/LED temperatures with large effects on the efficiency.

What is proposed is to construct three 6 x 8 in. 'best effort' avionic backlights using each of the three technologies, and to measure and report on their actual performance. This approach would help to demystify the relative efficiency of the various techniques, and help future display designers get the best out of their displays. 'Best effort' will involve a complex series of tradeoffs, and can only really be done by a displays manufacturer. It also needs to be done impartially—not by someone trying to sell a particular technology. Lamp length and diameter, cooling, and the shape and reflectivity of the cavity are some of the most important choices to be made, and there is little published information to guide the designer.

A possible extension to this aspect of the project would be to look at the use of two new lighting technologies: ultraviolet (UV) LEDs backlighting a white phosphor and vertical cavity surface emitting lasers (VCSELs). Using a white phospor to convert blue or UV radiation from LEDs has been said to be more efficient than using RGB LEDs to backlight a diffuser.

3.4 Reflective Color Separation Dichroic Filter Study by BAE Nashua (August 2003)

BAE SYSTEMS in Nashua NH rebuild its expertise in displays in early 2003 when Tom Gunn (a former Principal Investigator with Sanders on this HEAMLCD contract) was rehired and undertook a study of the RCS dichroic filter approach recommended by Dave Craig of BAE SYSTEMS in Edinburgh, UK (see Section 3.3.3.1 and Figures 25-26) to complete research under this HEAMLCD contract. Mr. Gunn's re-joining BAE Nashua was fortuitous because at about the same time Mr. Craig was assigned to a non-display project in a reorgnization at BAE Edinburgh. The RCS dichroic filter study was conducted by BAE Nashua during the Spring and Summer of 2003 and was summarized in a Dichroic Filter Study Report authored by Tom Gunn dated August 15, 2003 (the day the contract ended).

The RCS study was undertaken to evaluate the use of dichroic filters as part of an AMLCD display to increase its overall optical efficiency. The method, results, and discussion of this study are provided here. The implementation suggested is illustrated in Figure 26.

3.4.1 Design and Fabrication of RCS Dichroic Filter Breadboard. The preliminary design showed three components would need to be procured: (a) an AMLCD panel; (b) a patterned dichroic filter; and (c) a lens array. The AMLCD panel pixel dimensions were needed first to feed into the requirements for the patterned filter and lens array. An informal trade study of vendors for the three components was accomplished. For the AMLCD panel a vendor was sought with experience modifying off-the-shelf consumer-grade AMLCDs. White Electronics was selected for their experience and their offer of a sample display for free. This free display panel was a Sharp LCD Model LQ54D343 that had one line out, which would not affect the tests in any way. A set of driver electronics for the display was purchased from Avnet.

A plano/convex cylindrical lens array was designed at BAE SYSTEMS in Nashua NH. The final values needed for the lens design were set based on the pixel dimensions of the AMLCD panel. Several materials, construction methods and vendors for lens fabrication were explored for cost/schedule/technical impact. In order to fit within the available resources an acrylic lens direct cut by diamond turning was chosen. Corning Diamond Turning/NetOptix manufactured the lens array.

A number of dichroic filter manufacturers were explored. Ocean Optics was chosen for their technical capability and claimed short turn around time. Ocean Optics was to manufacture an RGB striped dichroic filter matching the pixel dimensions of the LCD panel. The final dichroic filter design looked slightly different from the initial concept while being a bit less expensive to manufacture and assemble while providing the same performance. The difference was that lens array had only one flat surface. Referring to Figure 26, the plano surface faces the LCD glass while the convex surface faced the dichroic filter. With only one surface to modify, the cost was reduced and glare was hopefully reduced. In a production lens array, either the LCD glass would be index matched or the intervening epoxy would be used to lessen the step index change.

Unfortunately, Ocean Optics was not able to meet the schedule they agreed to. Ocean Optics supplied a sample of a patterned filter that did not match the pixel pitch required to match the display panel. The Ocean Optics filter was useful to examine as a sample but difficult to use to take data. An alternative supplier was sought. By the time it was known Ocean Optics would not meet the schedule it was too late to order another custom patterned filter. A set of off-the-shelf 50 mm square red, green and blue *transmission filters* was procured from Andover Corporation. These filters enable some meaningful data to be taken, but did not enable exploration of all of the aspects of the custom patterned dichroic filter design.

3.4.2 Setup for RCS Dichroic Filter Data Collection. The Sharp LQ64D343 panel was mounted into an open enclosure with the driver electronics. The driver electronics consisted of a Digital View model ACG-1024 controller, an LS520 Inverter to power the fluorescent edge lighting, a digital OSD (manual display controls) and the associated cables. The electronics were powered using an Agilent laboratory variable switching power supply set at 12 V. The display was driven by a standard Dell desktop personal computer (PC) in VGA mode, 640x480 resolution, the native resolution of the Sharp display. This assembly was set on an optical table for vibration isolation.

A 1980-B spectra-radiometer mounted on an X-Z stage was set up adjacent to the optical table. The LCD panel was set on the table so the radiometer could take normal incidence measurements as illustrated in Figure 28.

The 1980-B was equipped with an MS-10X lens for close in work, enabling it to focus in on subpixels. Due to time constraints a computer control for the radiometer was unavailable. All work done was in photopic mode manually. A larger field-of-view lens would have been preferable to the 10X for the type of measurements taken but was not available. The 1980-B was used un-calibrated. For the purposed of comparisons within this set of data this lack of calibration is acceptable.
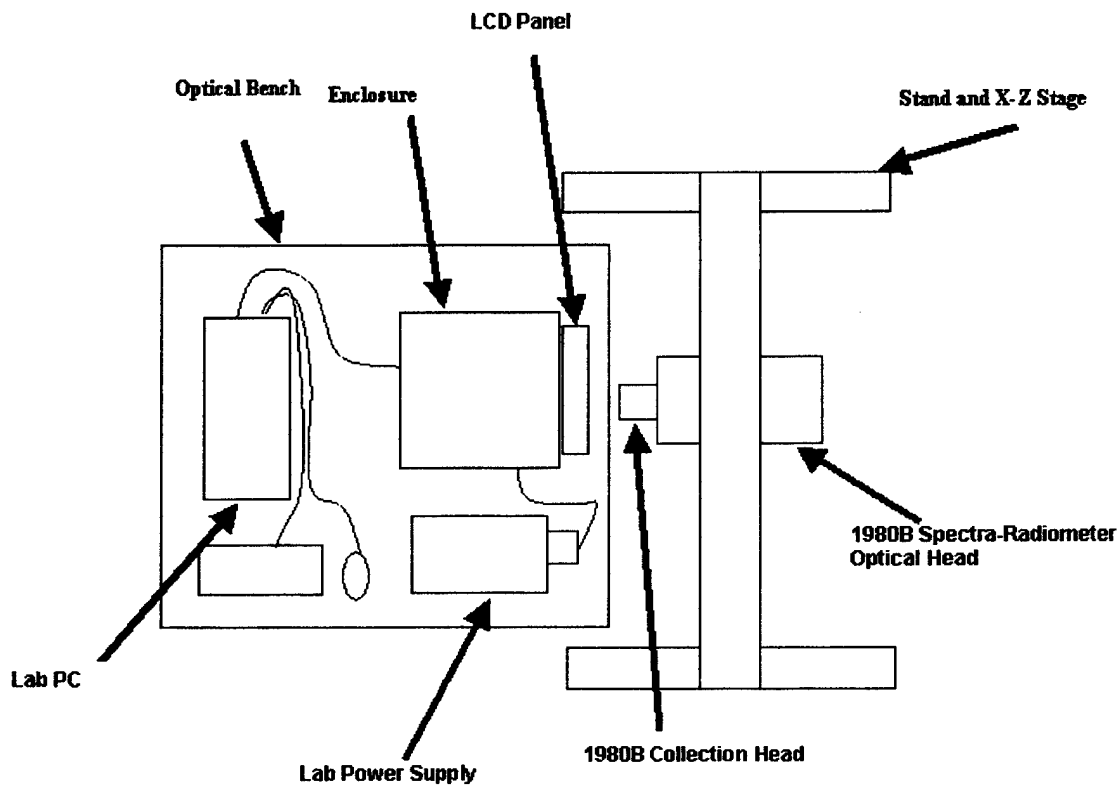
Figure 28: Lab setup for RCS dichroic filter study.

For each sample, the 1980-B had the same settings. A 2 arc minute aperture was used for all data samples. This allowed for subpixel sampling. The data samples consist of luminance measurement of individual red, green and blue subpixels. A number of samples of each configuration were taken for averaging. The sample pixels were distributed across the display in a random manor to avoid any pattern. Once a pixel was selected for measurement the red, green, and blue sub pixels were each measured.

The display was measured in several configurations. A set of three dichroic filters was placed within the display at several locations in the optical stack. The three dichroics were not stacked in the display, they were laid out next to each other as illustrated in Figure 29. The set of measurements planned to have been taken were as follows:

> Unaltered display;
> With the dichroics between the backlight and the other optical stack components;
> With the dichroics between the Brightness Enhancement Filter (BEF) and the Polarizer;
> With the dichroics between the Polarizer and the LCD Glass;
> With the dichroics between the Polarizer and LCD Glass, without the BEF;
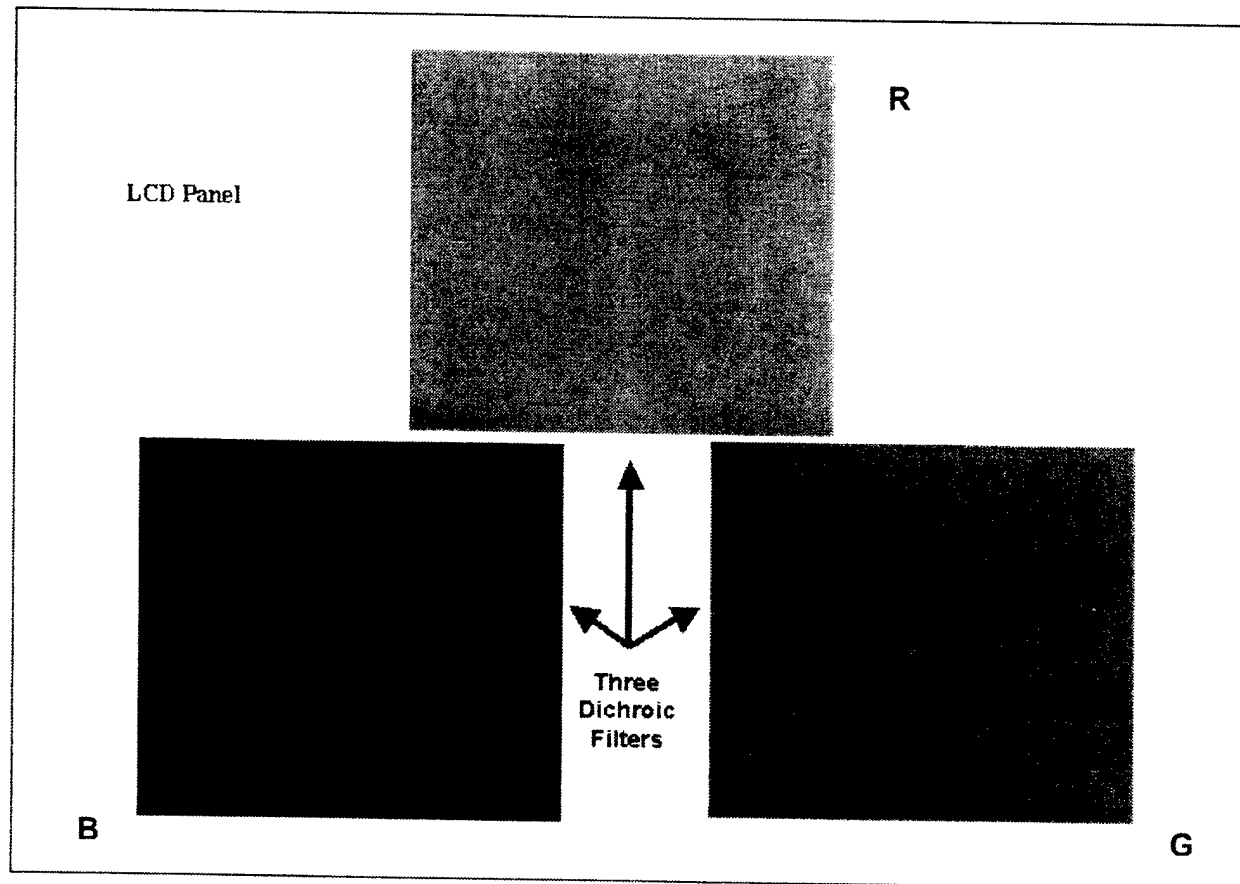> Without the Dichroics and without the BEF.

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Figure 29: LCD showing dichroic filter locations, when place in LCD

Within each set of data taken with the dichroic filters, measurements were taken both within the area of the filters placed as illustrated in Figure 29, and the unfiltered region. Data was taken with the display driven to full white (pixel value 255,255, 255 and full saturation) and to full black (pixel value 0,0,0 and 0 saturation). All data is reported in foot-Lamberts (fL).

A final note on the set up. The lens array was not, in the end, used in taking data because without the patterned filter it was unnecessary.

3.4.3 Data Analysis of RCS Dichroic Filter Experiment. The basis for taking the data set is as follows. The dichroic filters have a high transmission within their spectral range and a high level of rejection/reflection outside of that spectral range. They exhibit very little absorbance. The reflected light from the three dichroic filters is expected to increase the overall light available to other pixels as the light is recycled by the backlight. Placement within the optical stack will affect this overall benefit depending on how the light interacts with other optical filters.

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The consolidated and analyzed data collected is presented in Table 5. Each Row represents data from a one of the listed configurations. The columns identify the pixel measurement meaning. Individual measurements were averaged to arrive at this data. For the unfiltered data, taken in a region were there was no dichroic filter, data from all of the red subpixels was averaged, and again for the green and blue subpixel data. The sum of the red, green and blue subpixel data is shown as the luminance measurements in Table 5.

The synthetic pixel columns represent an attempt to show how these dichroic filters would perform if patterned to the subpixel as we had intended. The blue subpixel measurements from the blue filter region were averaged and counted as the blue subpixel for the synthetic pixel, similarly for the red and green subpixel for the synthetic pixel. These three numbers were then added together and count as the luminance of the synthetic pixel.

Data was taken of the "off" subpixels color in the dichroic filter regions as well. The "off" pixels are, as an example, the red and green subpixel in the blue filter region (the subpixel data not included in the "synthetic" pixel). The off-pixel data basically represent the difference in spectral characteristics of the dichroic filter and the dye filter of the AMLCD. It may be possible to use this data to analyze the interaction between the dichroic filter and the BEF. Off the shelf filters were used and it was necessary to take what was available on short notice. If used in a production display the filters would match more closely.

This procedure was followed with the display driven full "on" for white; and "off" for black. The ratio of these two measurements is the contrast ratio.

Table 5: Consolidated data and analysis for experiment on RCS dichroic filter approach

	Luminance Unfiltered Region White Pixel (fL)	Luminance Synthetic Cell White Pixel (fL)	Luminance Unfiltered Region Black Pixel (fL)	Luminance Synthetic Cell Black Pixel (fL)	Contrast Ratio Unfiltered Region	Contrast Ratio Synthetic Cell
Unaltered Display	17.62		0.24		72.90	
Dichroic's behind BEF and Polarizer	20.00	14.86	0.28	0.20	70.85	75.75
Dichroics between BEF and Polarizer	21.15	14.97	0.27	0.20	77.82	74.05
Dichroics between polarizer and glass	21.11	14.78	0.31	0.21	67.57	71.76
Dichroics between polarizer and glass, no BEF	17.23	12.99	0.30	0.20	57.77	64.00
No Dichroics, No BEF	14.31		0.26		54.38	

The unaltered display has a luminance of 17.62 and a contrast ratio (CR) of 72.90. The panel specifications call out a CR of 100 or better. The measurements taken are close but do not show a CR of 100. The difference may be in calibration. The radiometer should be re-calibrated for use in measuring significantly different light intensities. It is also possible the panel was out of specification. In either case this data is still valid for comparisons *within* the data set.

The question is: "Do the dichroic filters work as promised?" There is some evidence here that they will. One can see that in the unfiltered region the pixels are brighter. A comparison of the

unaltered display "Luminance Unfiltered Region White Pixel" with the three following cases, 17.62 fL vs. 20 fL, 21.15 fL and 21.11 fL, shows light reflected by the dichroic filters is being recycled and reflected back out. However, not as much light is reflected back out as one would anticipate if the light were fully recycled.

One cause of this is the backlight is not highly efficient at recycling light. Qualitatively it was obvious as we could see cyan, yellow and magenta light coming out the backside of the backlight where the dichroic filters were located. This corresponds to the reflected light expected from the dichroic filters. The fixture used had made it difficult to measure the backside output but it was estimated that another 10-20% improvement could be made in luminosity with a more efficient reflective backlight cavity. The cost would be increased volume and weight. A trade could be made but certainly current industry practice is to keep LCD's thinner and lighter.

No improvement is found in the synthetic pixel luminance data. In fact, a loss relative is observed to the unaltered LCD. This loss can be partially be explained by the nature of the off-the-shelf dichroic filters used. The average transmission was in the 93-94% range. The in-band loss could account for a portion of the difference and another portion can be attributed to the slight spectral miss-match between these off-the-shelf filters and the LCD color gel filters. In addition, the less then optimal backlight efficiency also has an impact.

The Ocean Optic dichroic filters are better and will help improve the performance but not enough. The Andover Filter Transmission curves and the Ocean Optic Transmission curves are presented in Figures 30 and 31, respectively. Reflectance data has been requested to allow for a full analysis.

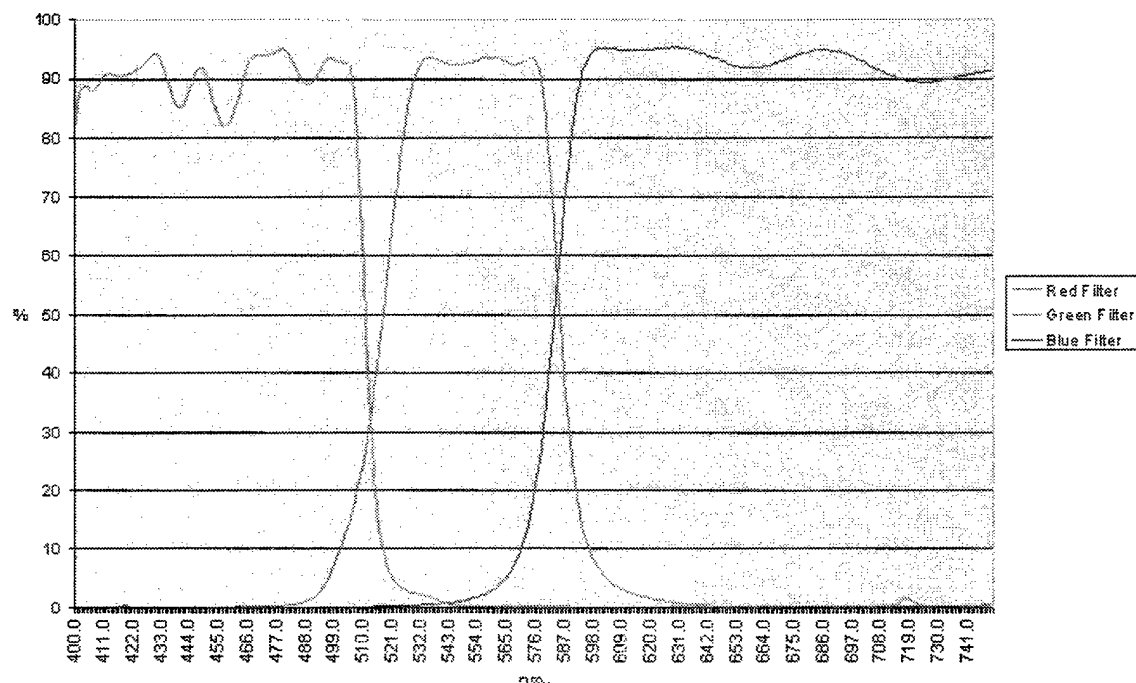**Andover Dichroic Filters Transmission Curves**

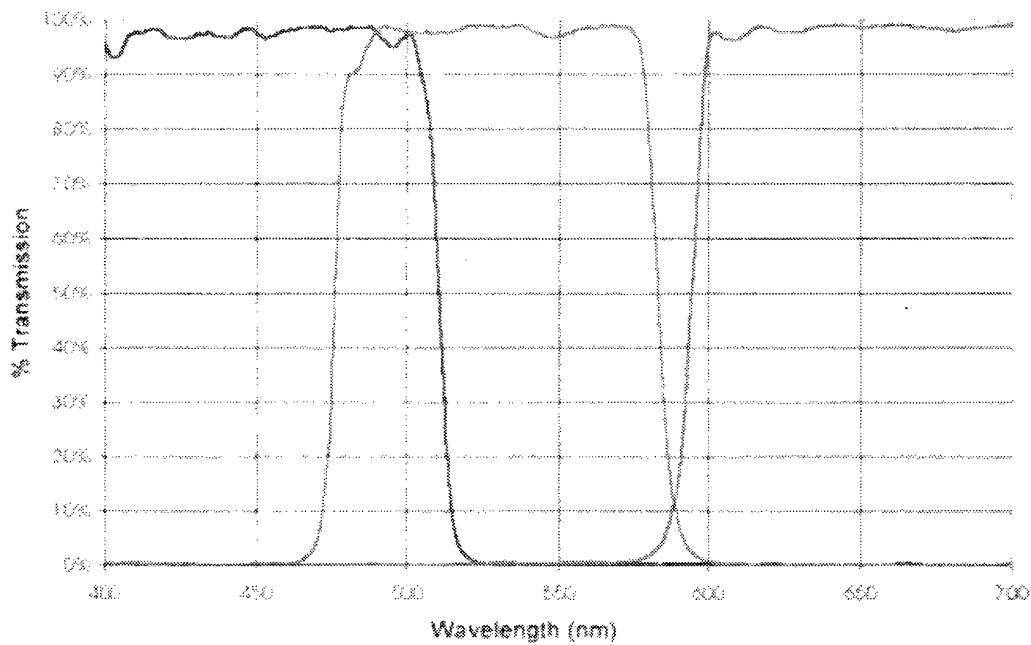Figure 30: Transmission Curves for Andover Dichroic Films

Figure 31: Ocean Optics Transmission Curve

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One other theory that may account for less improvement in the synthetic pixel luminance is the interaction with the reflective polarizer. This display uses a reflective polarizer in addition to the BEF to enhance brightness. The reflective polarizer reflects light of the unused polarization state back to the backlight to be recycled, which is what was attempted with the dichroic filters. This kind of filter had been considered at the inception of this program but was dropped to focus on the DCS approach. In the mean time, the industry has perfected the technique.[12]

In considering the interaction with the reflective polarizer there are two cases to consider. The first case is the polarizer in front of the dichroic filter, relative to the front of the display. Light passing through the dichroic filter will hit the reflective polarizer; a portion will pass through, about 45% and the rest will be reflected back toward first the dichroic filter and then the backlight. The dichroic filter is bi-directional so this reflected light from the polarizer would again be partially reflected, this time spectrally selective. Note that the dichroic filter will reflect from the front side the same way as it does from the rear side, red will reflect cyan, blue will reflect yellow, and green will reflect magenta. These are the opposite colors one wants in the selected pixels. Overall this interaction appears to reduce the reflective polarizer efficiency gain more then the dichroic filter helps improve the brightness.

Similarly, if one places the dichroic filters in front of the polarizer, the two interact in a way that is difficult to predict. Light reflected by the dichroics is partially reflected off the polarizer, as some of the light must be undergoing some polarization rotation at the dichroic reflection. This phenomenon is seen in the reduced contrast ratios of the cases where the dichroic filters are in front of the polarizer.[13]

Another consideration is the backlight position. The Andover filters are on a relatively thick substrate, 1 mm, relative to the display. In placing the dichroic filters in the display the backlight injecting light into the display was altered a bit. From a quantitative perspective, it appeared to be acceptable but it may be that enough light leaked out that it affected the measurements.

One additional non-quantitative observation is that the dichroic filters have a narrow angular range over which they work as intended. This narrow angular range evidences itself in color inversion at angles lower then display area not covered by the dichroic filters. It was estimated that the angle is half of the unaltered parts of the display, or about 30°. This affect is satisfactory in some applications. However, the off color reflection mentioned earlier will be more of a problem for avionics displays due to the high ambient light conditions.

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[12] See, for example, the 3M Corp. "Vikuity" product line.

[13] It had been intented to replace the reflective polarizer with a non-reflective type to explore this hypothesis, but once all of components were available there was insufficient time to run this test.

4. CONCLUSIONS

The DCSF diffraction results show an orderly arrangement of colored spots in a variety of samples as illustrated photographically in Figures 4, 9, 19, and 21. The physics of the DCSF clearly shows promise. However, the tools, processes, and techniques available during this effort proved to be insufficient to the task of fabricating the DCSF as designed.

As shown in Figure 19, some of the spots for MEMS Optical wafer W20, their best attempt as of August 2001 to fabricate the DCSF, are masked on the left end of each color strip by a smearing of light. This smearing can be correlated to the same location on the left end upper corner of each of the imaging lenslets (see Figure 20). The cause of this smearing artifact is yet to be determined. The DCSF wafer W20 meets just 1 of 16 of the relative color band dispersion specifications in the SoW given to MEMS Optical by BAE Nashua in 1997 (see Table 2). The problems evident in wafer W20 could be a function of the etch aspect and structure as suggested by MEMS Optical in their recommendations specific to the etch quality (see Section 5 below). Unfortunately, a discussion with MEMS Optical was not accomplished by BAE Systems to clearly identify the location of the red, green, and blue sub-apertures for the wafer W20 diffraction pattern and how it lines up precisely with the LCD pixel format.

The DCS approach to HEAMLCD requires a collimated backlight, DCS filter, and a low reflectance diffuser. With modifications a DCS is assessed to be is feasible. Also, the collimated backlight to be achievable; both CCL and LED backlight approaches are feasible. However, the low reflectance diffuser appears not to be feasible. Thus, the overall conclusion is that the DCS approach to HEAMLCD is *not feasible* with current optical materials, components, and fabrication technology.

The short study conducted for the RCS dichroic filter approach was insufficient in scope to conclude if dichroic filters improve the efficiency of direct view LCD's or not. The evidence that was obtained suggests that the answer is no. However, another study using the fully patterned improved transmission filter from Ocean Optics or a similar vendor may show sufficient promise for further investigation. It appears that for large (> 10 in.) backlight displays the combination of reflective polarizer and BEF give more efficiency gain for a lower cost then dichroic filters would.

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5. RECOMMENDATIONS

5.1 MEMS Optical Recommedations to Improve DCS Filter Fabrication (August 2001)

Relaxing of the focal length requirements would alleviate some of the DCS filter design issues. The short focal length design requires the 1X high-frequency grating design. The 1X high frequency grating design has a fairly high aspect ratio between the horizontal step size and the vertical step height in the grating steps. High aspect ratio features are difficult to achieve in and of themselves. They are more difficult to achieve in a single grayscale pattern when coupled with the pattern height required for the focusing element. Therefore, patterning the grating-lens combination in a 2X lower frequency grating may yield sharper features because the feature aspect ratio should be at least one-half that of the 1X design.

Locating the focusing elements and gratings on opposite sides of the substrate is another method to relax system design constraints. By decoupling the lenses from the gratings, the overall etched height of the structure is smaller because the grating and the lenses would be etched separately. The current design requires that the grating and lens be etched together and, thus, doubles the height of the grayscale structure. As the grayscale structure increases in height, the ability to maintain sharp features in the lithographic process decreases. If the two optical element structures are decoupled the sharpness of the features of the grating and of the lens will both increase (although separately).

Both of the above-mentioned relaxation methodologies have been separately demonstrated to some degree in two of our previous design trades: (a) the binary multi-layer pattern and (b) the 2X grating-lens combination pattern. Some combination of the two methodologies yet may prove the feasibility of the DCSF concept in a production market.

A third alternative would be a two-surface design as mentioned above, using a 1X-stepper to produce a multi-layer binary on one side and a grayscale lens set on the opposite side. This alternative has the advantage of having high-resolution binary structures shot with good alignment accuracy. The lens resolution and alignment requirements are much more relaxed in this two-sided approach and, thus, the lens side of the optic should be simple to manufacture.

5.2 BAE Edinburgh Recommendations on All HEAMLCD Approaches (August 2002)

The DCS filter approach to improving AMLCD efficiency requires three elements to succeed: (a) a collimated backlight; (b) the DCS filter or RCS filter; and (c) a low reflectance diffuser screen.

An effort should be undertaken to further explore the correct fabrication of the DCS and RCS filters as described in Sections 3.3.1 and 3.3.3.1, with each taken in phases. The tools, processes, and techniques for DCSF fabrication need to be improved to enable it to be produced as designed. The grating etch process needs to be improved for sharper slopes.

Separately, an effort should be undertaken to address a variety of reflection reduction techniques, seven in all, as described in Section 3.3.3.2.

An effort should be undertaken to compare three backlight techniques for avionics AMLCDs: standard CCL, inorganic LED, and UV as described in Section 3.3.3.3. The LED light source alternative approach to increase AMLCD efficiency would use R,G,B LED light sources which have narrower spectral bandwidths than the color filters now used in mass production AMLCD designs. The recent advent of RGB inorganic LED illumination availability in the market suggests an experiment on the DCSF with this illumination, as illustrated in Figure 23. The individual R,G,B light diodes are compact and have spectral bandwidths that are advertised to be non-overlapping and are compatible with the BAE Nashua SoW written in 1997 for vendors tasked with the fabrication of DCSFs. The RGB illumination of the DCSF should be investigated for compliance to the BAE Nashua DCSF SoW and in easing etch design requirements.

A critical technology challenge is presented by the required, but unavailable, low reflectance diffuser screen. Indeed, it was determined in August 2002 that this component is not feasible base on the current state-of-the-art. An effort should be undertaken to develop low reflectance diffuser screen technology to enable success of the overall DCS approach to HEAMLCD.

5.3 BAE Nashusa Recommendations on RCS Dichroic Filter Approach (August 2003)

Additional work would be useful to address questions that arose during the RCS dichroic filter study. Testing with a non-reflective polarizer would be useful in order to separate out the affects of the reflective polarizer verses the reflective dichroic filter. Tests with a fully patterned dichroic filter and customized backlight would also help clear up the remaining questions. Spectral data should be gathered to quantitatively examine the affects of the dichroic filter on the display color range, especially at angles off of the normal to the display surface.

The dichroic filter vendor, Ocean Optics, is pursuing display applications and is having some success in the areas of projection and direct-view visual systems. Their success in deploying dichroic filters in LCDs should enable their use in future avionics AMLCD programs.

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6. LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

ACA	Addressed cell assembly (LC-filled cell of two edge-sealed plates, typically glass, with an addressing electrode (PM or AM) having been fabricated on each plate; may include optical features such as polarizing filters, by lamination or design)
ACS	Active color separator (initial MEMS design in 1996)
AFM	Atomic force microscope, atomic force microscopy
AFRL	Air Force Research Laboratory
AFRL/HEC	AFRL Crew System Interface Div. (established FY1998; includes Visual Display Systems Branch, AFRL/HECV, comprising former AL/CFHV & WL/AAJD)
AG	Anti-glare (coating)
AM	Active matrix (electronic backplane w/ address voltage memory at each subpixel)
AMLCD	Active matrix liquid crystal display
A/R	Anti-reflective (coating)
ASTARS	A Science and Technology Activity Reporting System
B390	Blue color filter centered at 390 nm
BAA	Broad Agency Announcement (RFP for multiple topics)
c	Speed of light in a vacuum = 3×10^8 ms^{-1}
CCD	Charge-coupled device
CCL	Cold cathode lamp
CE	Contrast enhancement
CHF$_3$	Trifluromethane molecule
CP	Circular polarizer, polarizing
CSF	Color separation filter
D65 white	White light having a (Red:Green:Blue) luminance ratio of (22:75:3)
DARPA	Defense Advanced Research Projects Agency
DCS	Diffractive color separation (synonym for ICS)
DCSF	Diffractive color separation filter (synonym for ICSF)
DHA	Display head assembly (e.g. AMLCD
DOC	Diffractive Optics Corporation
DoD	Department of Defense
DTIC	Defense Technical Information Service
DVC	Displays Viewability Consortium (U.K.)
EM	Electromechanical (display technology)
FPD	Flat panel display (synonym for AMLCD; generally, any LCD, plasma, OLED)
G530	Green color filter centered at 530 nm
HDS	High Definition Systems (DARPA program)
HEAMLCD	High efficiency AMLCD
HIM	High index (of refraction) material, where index = c / (light velocity in material)
ICS	Interference color separation (synonym for DCS)
ICSF	Interference color separation filter (synonym for DCSF)
ILED	Inorganic light emitting diode
JND	Just noticeable difference (in luminance)
JON	Job Order Number
LC	Liquid crystal (material, special mixture of components, chemical recipe)
LCD	Liquid crystal display

LED	Light emitting diode (assumed to be inorganic if not stated otherwise)
LIM	Low index (of refraction) material, where index = c / (light velocity in material)
LM	Lockheed Martin (owned Sanders Avionics Division in Nashua from 1995-2000)
LRU	Line replaceable unit (e.g. avionics box containing integrated display, electronics)
LVPS	Low voltage power supply
MEMS	MEMS Optical Inc., the micro-optical manufacturing subsidiary of SY Technol.
MTBF	Mean time between failure
η	Index of refraction of a material (medium) = $cv^{-1} = (\varepsilon\mu)^{1/2}$, where ε = dielectric constant (permittivity) & μ = magnetic permeability of the medium
ND	Neutral density (filter that absorbs all visible light wavelengths equally)
nit	candela per square meter (standard unit for luminance), $cd\ m^{-2}$
NRE	Non-recurring engineering (cost)
NTSC	National Television Standards Committee U.S. TV broadcast standard (525 lines, 336 spots/line, interlace scan)
O_2	Oxygen molecule
OEM	Original equipment manufacturer
OLED	Organic light emitting diode
PJND	
PM LCD	Passive matrix LCD (no addressing voltage memory, operated by impulse signals)
PRDA	Procurement Research and Development Announcement (RFP on a specific topic)
RCS	Reflective color separation
RE	Recurring engineering (cost)
RFP	Request for proposals
RGB	Red, Green, Blue
R60	Red color filter centered at 600 nm
SDR	System Design Review
SiO_2	Silicon dioxide
SoW	Statement of Work
SY	SY Technologies Inc. in Huntsville AL
TAA	Technical Assistance Agreement (TAA) from Departments of State and Defense (required to perform DoD funded research in U.K.)
Ta_2O_5	Tantalum oxide (full chemical name: ditantalum pentoxide)
TFT	Thin film transistor (most common form of active matrix device in AMLCDs)
TIP	Technology Investment Plan
U.K.	United Kingdom of Great Britain and Northern Ireland
UV	Ultraviolet (light)
VCSEL	Vertical cavity surface emitting lasers
WL	Wright Laboratory (consolidated into AFRL during FY1998)
WL/AAA	WL Systems Avionics Division (included Cockpit Avionics Office, WL/AAA-2)
WL/AAJ	WL Electro-Optics Systems Division (included Displays Branch, WL/AAJD)
1X DCSF	high frequency grating design for diffractive interferometric color separation filter contains no focusing elements; feature aspect ratio is high, focal length is short
2X DCSF	low frequency grating design for diffractive interferometric color separation filter contains refractive lens element for focusing desired color band through the designated subpixel strip of each LCD pixel; feature size is twice that of 1X, feature aspect ratio is one-half that of 1X

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APPENDIX A.

LIST OF PATENTS OBTAINED WITH SUPPORT FROM THIS PROGRAM

"Light collimator for liquid crystal displays"
Inventors: Gunn; Thomas V. (Candia NH); Halstead; Wesley H. (Sammamish WA)
Assignee: BAE SYSTEMS (Nashua NH)
US Patent 6,464,365 issued 10-25-02

"Trimodal microlens"
Inventors: Gunn; Thomas V. (Candia, NH); Schmidt; Michael P. (Hollis NH); Halstead; Wesley
H. (Sammamish WA); Hicks; Richmond F. (Nashua NH)
Assignee: BAE SYSTEMS (Nashua NH)
US Patent 6,487,017 issued 11-26-02

"Sunlight viewable color liquid crystal display using diffractive color separation microlenses"
Inventors: Gunn; Thomas V. (Candia NH); Schmidt; Michael P. (Hollis NH)
Assignee: BAE SYSTEMS (Nashua NH)
US Patent 6,618,106 issued 9-9-03

APPENDIX B.

LIST OF PUBLICATIONS REPORTING WORK SUPPORTED BY THIS PROGRAM

Rich Hicks, "A new architecture for high efficiency AMLCD's," in *Cockpit Displays III*, Darrel G. Hopper, Editor, Proceedings of SPIE Vol. 2734, pp. 46-56 (1996). Available from www.spie.org .

Richmond F. Hicks, Wes Halstead and Thomas Gunn "Diffractive color separation for high efficiency LCD's," in *Cockpit Displays IV: Flat Panel Displays for Defense Applications*, Proceedings of SPIE Vol. 3057, pp. 200-211 (1997). Available from www.spie.org .

Thomas V. Gunn and Wes Halstead, "Diffractive color separation fabrication," in *Cockpit Displays V: Displays for Defense Applications*, Darrel G. Hopper, Editor, Proceedings of SPIE Vol. 3363, pp.198–208 (1998). Available from www.spie.org .

Peter S. Erbach, Gregg T. Borek, David R. Brown, and Tom Gunn, "Diffractive color separation filter for high efficiency LCD panels," in *Flat Panel Display Technology and Display Metrology*, Bruce Gnade and Edward F. Kelley, Editors, Proceedings of SPIE Vol. 3636, pp. 48-59 (1999). Available from www.spie.org .

APPENDIX C.

TECHNICAL PAPER: "DIFFRACTIVE COLOR SEPARATION FILTER FOR HIGH EFFICIENCY LCD PANELS" (SUMMARY OF 1998 RESULTS)

This appendix is a paper reporting in work accomplished in 1998 under this contract and published by SPIE—The International Society for Optical Engineering by three personnel at MEMS Optical Inc. with one co-author from BAE SYSTEMS (then Sanders, a Lockheed Martin Co.). This paper summarizes work by MEMS to design, fabricate and test diffractive color separation filters (DCSF) through December 1998 under its subcontract to BAE SYSTEMS as part of this HEAMLCD contractual effort; the paper citation is as follows:

> Peter S. Erbach, Gregg T. Borek, David R. Brown, and Tom Gunn, "Diffractive color separation filter for high efficiency LCD panels," in *Flat Panel Display Technology and Display Metrology*, Bruce Gnade and Edward F. Kelley, Editors, Proceedings of SPIE Vol. 3636, pp. 48-59 (January 1999).

This paper was also presented orally at the SPIE Photonics West Symposium in January 1999.

Appendix C is not subject to any distribution restriction.

Many figures have been enlarged to aid readability.

Diffractive color separation filter for high efficiency LCD panels

Peter S. Erbach[a], Gregg T. Borek[a], David R. Brown[a], and Tom Gunn[b]

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95 Canal St., Nashua, New Hampshire, 03061

ABSTRACT

Current AMLCD panel pixels are divided into sub-pixels each covered by red, green, or blue absorptive color filters to transmit each of the color components. This method discards 2/3 of available light and causes these displays to be highly inefficient. Using a diffractive color separation filter, DCSF, a much higher percentage of energy from the back-light is used in the display, which can be translated into higher brightness and lower power consumption. Such a DCSF is designed to separate the colors and focus the desired bands onto the apertures of the color pixels. The black matrix is used to block the undesired wavebands. Two basic prototype models were designed and fabricated. The first filter design contains focusing elements and the second filter contains no focusing elements. This paper presents testing results from the two prototype diffractive color separation filter designs.

Keywords: Diffractive optic, flat panel displays, LCD, color separation filter, high efficiency

1. INTRODUCTION

The operation of the DCSF is simple in nature as shown below in Figure 1. A more detailed description of the intended operation can be seen in the references.[1] We assume three color bands in the collimated white light source. Each color band in the white light encounters a slightly different material index of refraction. Therefore, the wavefront (phase surface) for each color band is shaped to propagate the light in a different direction.[2] The DCSF is designed so that the red light propagates through to the −1 order and it passes through a red sub-pixel (color-stripe) in a LCD display (see Figure 1b). The green light propagates to the 0 order and it passes through a green sub-pixel in a LCD display and the blue light propagates to the +1 order and it passes through a blue sub-pixel in a LCD display. This system design was initially developed by Sanders, a Lockheed-Martin Company. Sanders has contracted with MEMS Optical concerning DCSF design and fabrication.
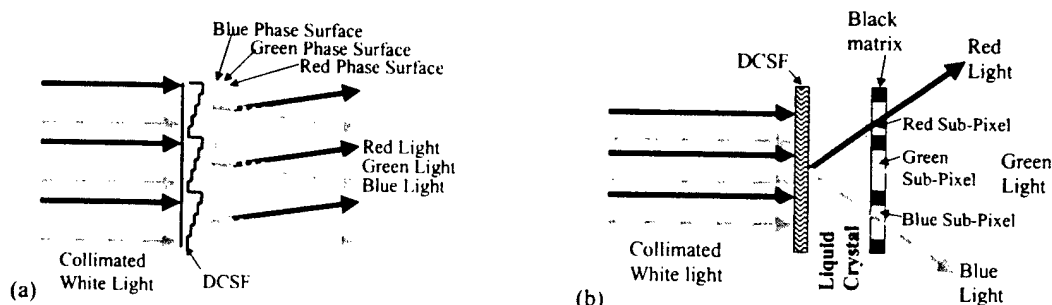

Figure 1. DCSF theory of operation

2. RESULTS

This section details the test methodology and test results from various DCSF designs. Each design utilized the same basic structure. The designs are different in their feature size and focusing elements: design #1 has features that are half the size of the features in design #2. These designs are called 1X and 2X, respectively. Design #1 contains no focusing elements and design #2 contains refractive lens element for focusing the desired color band through the designated color stripe of each LCD pixel.

The performance metric for these tests is described in terms of SNR and Efficiency as follows:

$$SNR_{Red} = \frac{Power_{Red}}{Power_{Green} + Power_{Blue}} \qquad (1)$$

where the red, green, and blue subscripts represent the LCD (color stripes), or the −1, 0, and +1 diffraction orders. SNR_{Green} and SNR_{Blue} are defined similarly. Efficiency is defined as

$$EFF_{Red} = \frac{Power_{Red}}{Power_{Red,Undeviated}} \qquad (2)$$

EFF_{Green} and EFF_{Blue} are defined similarly.

These metrics essentially compare the power in the desired color-band (signal) to the power in the undesired color-bands (noise) for each red, green, and blue sub-pixel for a color-stripe pixel. These metrics also compare the diffracted power in the desired color band to the undiffracted power in the desired color band.

The test configuration for the 1X design is shown in Figure 2 and the test configuration for the 2X design is shown in Figure 3. In each configuration, a Fibre-Lite source was used as the white light source and the source light was collimated using a positive lens placed a focal length away from the source. The Fibre-Lite source spectrum is shown in Figure 4. It can be seen that the source has a great deal of power in the red portion of the spectrum. Neutral density (ND) filters were used to prevent saturation of the CCD. The ND filter transmission values were verified using a HeNe laser and a Newport model 835 optical power meter with a Newport model 818-SL detector head. The mean % Error between the stated and measured transmission values for the ND filters used was approximately 5.5%.
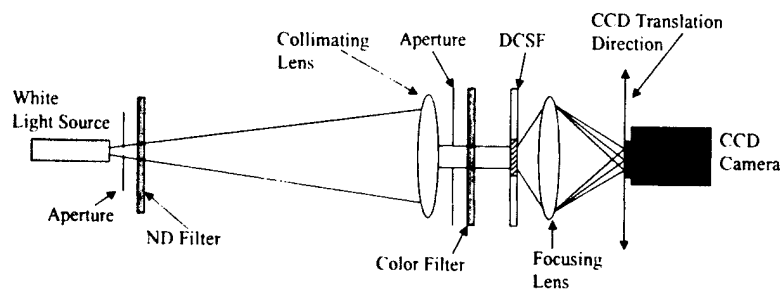
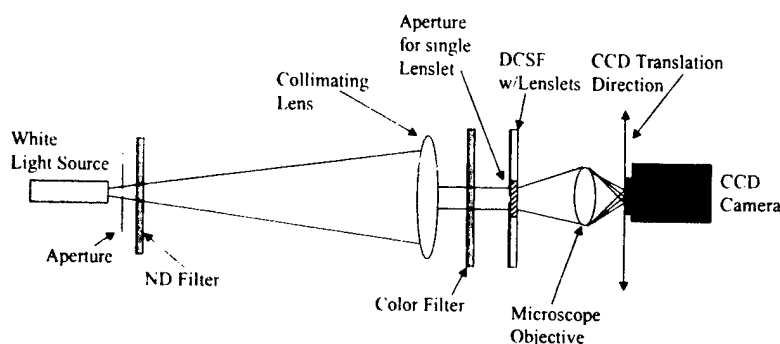Figure 2. Test configuration for the 1X DCSF design

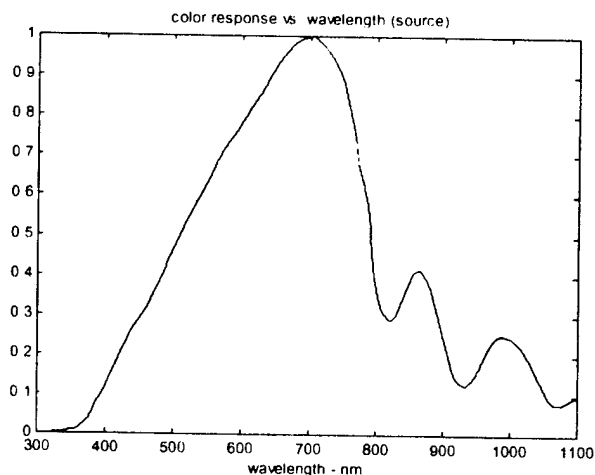Figure 3. Test configuration for the 2X DCSF design

Figure 4. Relative source spectrum

The collimating lens in the 1X test configuration has a focal length of 750mm and the collimating lens in the 2X test configuration has a focal length of 1000mm. A color filter is placed in front of the DCSF to prevent light outside of a desired color-band from reaching the CCD camera. The color filters were Hoya R60, G530, and B390 glass color filters. The color transmission characteristics of each filter are shown in Figure 5. The quoted transmission characteristics for the color filters were only given over a range of 300nm to 750nm. Therefore, the color filter responses were extrapolated to 1100nm to match the quoted source and camera spectral response data. The extrapolation was performed using a linear prediction function in MathSoft's Mathcad software.

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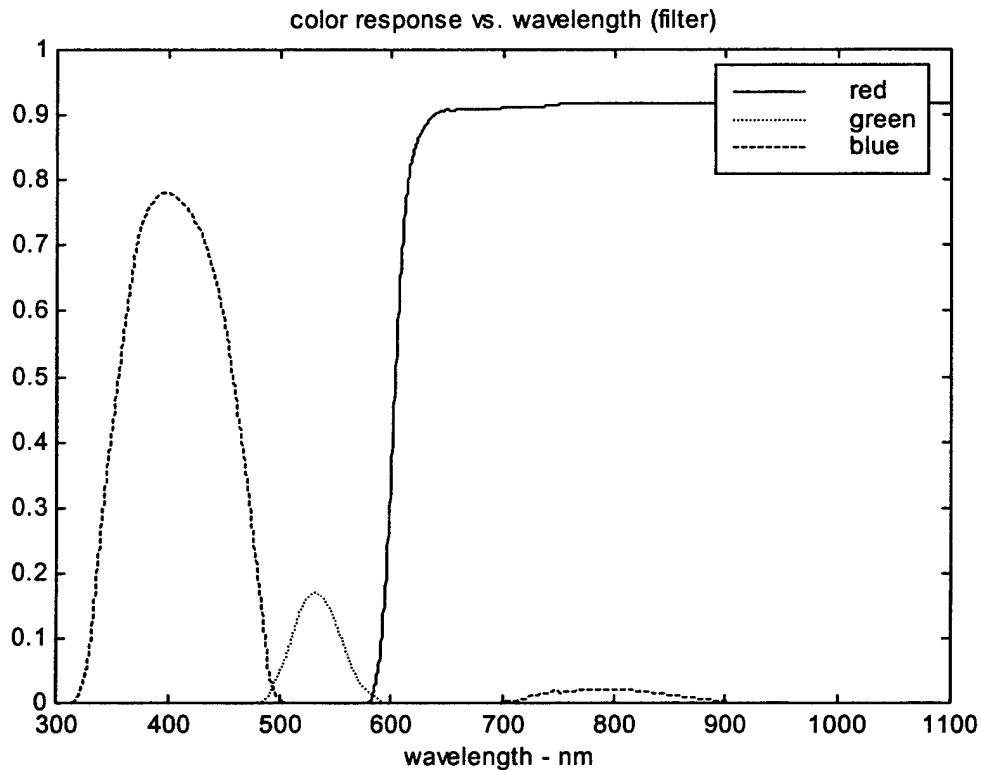
Figure 5. Filter color response (transmission)

An aperture was placed in front of the color filter in the 1X DCSF test configuration to reduce the beam size incident on the optic. Here the focusing lens acted like the lens element in the 2X DCSF design and the beam size determined the lens aperture. A slit aperture was placed against the 2X DCSF so that the throughput for just one lens element on the DCSF could be examined. The etched surface of each DCSF was placed away from the source.

The focusing lens used in the 1X DCSF test configuration was a 50mm positive lens to focusing the light emerging from the 1X DCSF to fit onto the CCD camera array vertically and to reduce the translation requirements for the camera. This was required because there was no focusing element integrated into the DCSF as in the 2X DCSF design. The 2X DCSF test configuration employed a 10X microscope objective instead of the focusing optic. The objective reimaged the focal spots produced by the 2X DCSF design onto the CCD camera array, otherwise the camera array could not be translated close enough to the optic to image the focal spots. The CCD camera used for the 1X DCSF test configuration was a SONY model XC-77 monochrome camera with 8.4 micron pixels. The CCD camera used for the 2X DCSF test configuration was a Photon model 2321 BeamPro$_{filer}$ Laser Sensor monochrome camera with 11 micron pixels. The quoted camera spectral responses actually started at 400nm, so these had to extrapolated backwards to get data beyond 400nm. The relative color responses for the Photon and Sony cameras are shown in Figure 6.
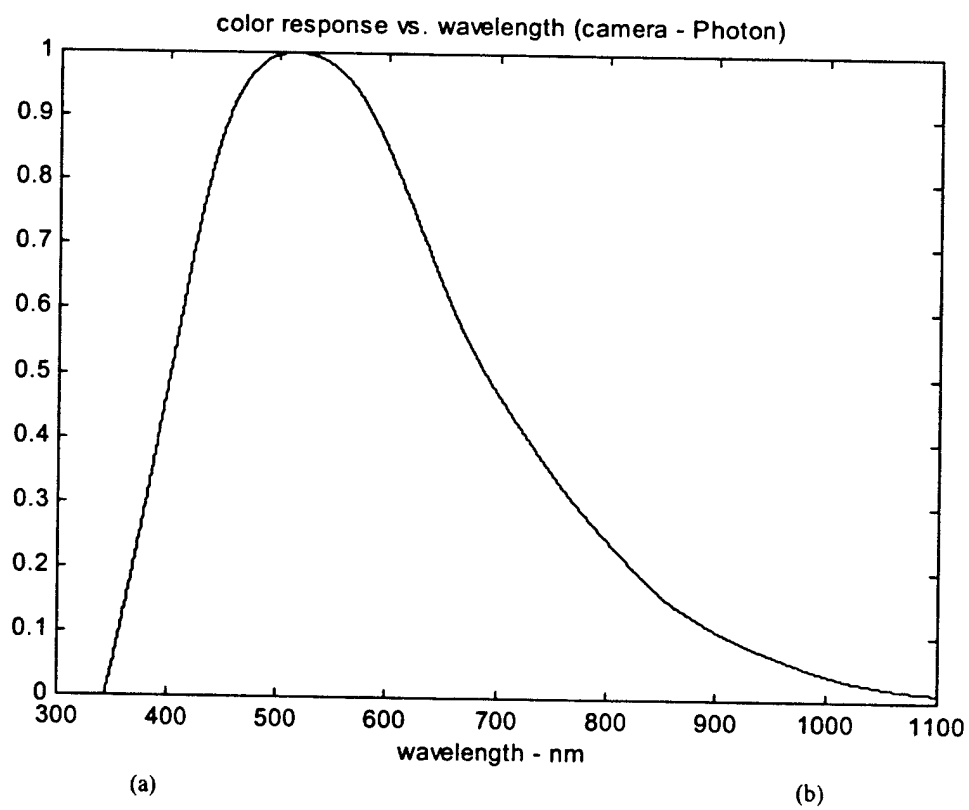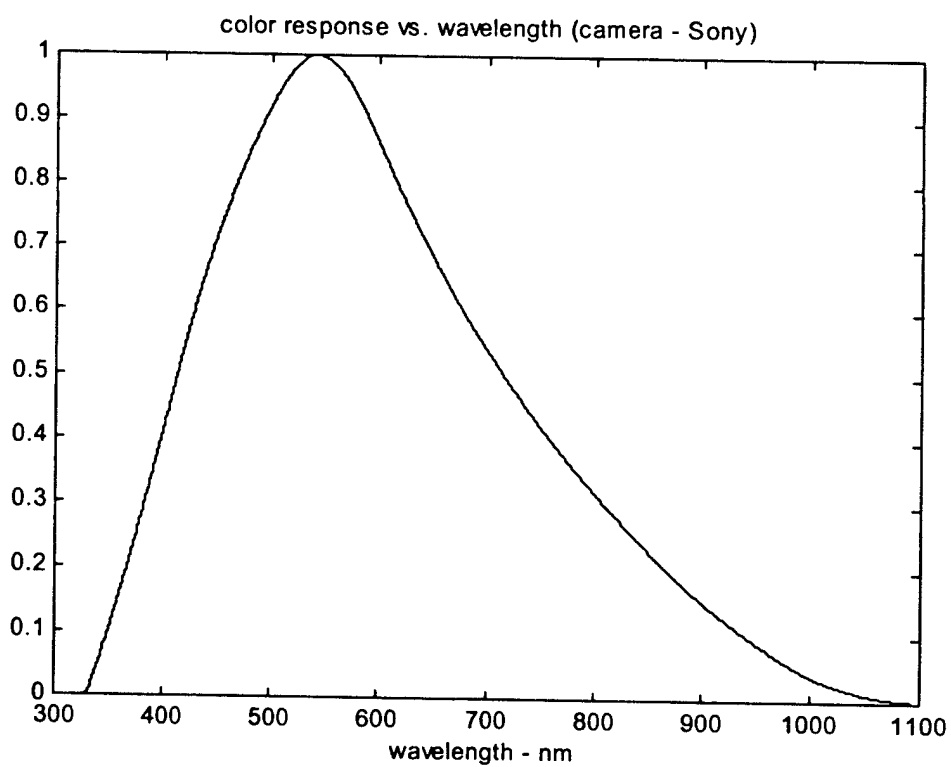
Figure 6. (a) Sony CCD camera relative color response and (b) Photon CCD camera relative color response

In each configuration, the CCD camera was translated in a direction parallel to the color separation produced by the DCSF. The CCD camera was scanned across the focal plane for each color filter. The irradiance patterns detected by the cameras were captured with Matrox Genesis frame grabbers and were subsequently "stitched" together using Matrox Inspector and Math Works Matlab software. Figure 7 shows examples of the scans captured using the 1X test configuration. Note that the "stitchings" are not perfect because the DCSF diffraction axis is slightly tilted with respect to the camera array horizontal axis.
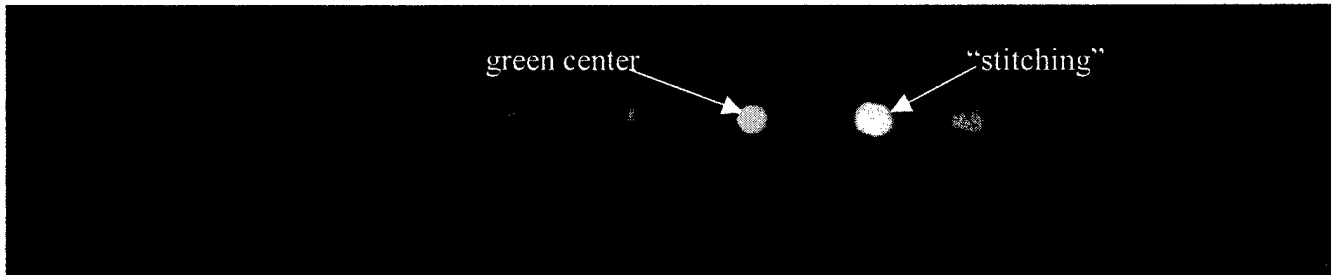
Figure 7. Scanned blue irradiance pattern for the (a) 1X DCSF design. The ND value was 0.5 (i.e., the transmission was $10^{-0.5}$)

These images were thresholded to remove noise. This was done for every set of images. Image noise was extracted from the top and bottom of the images. The noise threshold τ was then calculated by using

$$\tau = \mu + 4 \cdot \sigma \qquad (3)$$

where μ is the noise mean and σ is the noise standard deviation. Pixel values above τ were reduced by τ and pixel values below τ were set to zero.

The center of each image set was determined using the Matrox Inspector software. The center focal spot of the green images was determined (the optic is designed to transmit green light parallel to the optic axis) and the green focal spot centers of the blue and red images were determined. The red, green, and blue images for each set were centered with respect to each other. This is shown for a tilted 2X design in Figure 8 (these are portions of the full image).
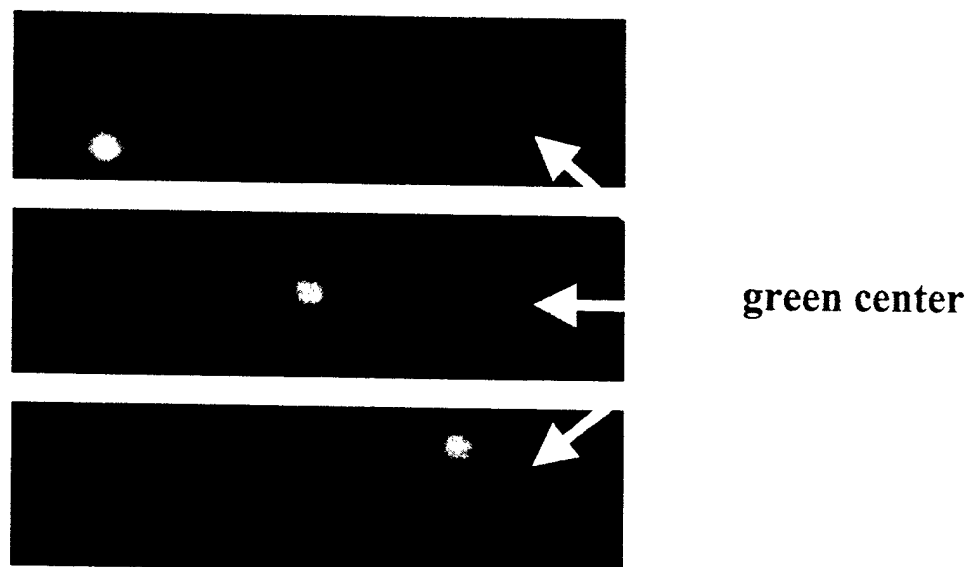

green center

Figure 8. Beam centering in a 2X test configuration for a Tilted 2X design (green and blue images are slightly contrast enhanced)

The normalized power in the -1, 0, and +1 order (-1 = red, 0 = green, +1 blue) diffraction orders were calculated. This normalized power was calculated because absolute measurements were not obtained with the CCDs. This measurement is calculated using

$$Power_{Normalized} = \oint_{ROI} Irradiance_{Normalized} \cdot dA \qquad (4)$$

Irradiance$_{Normalized}$ is calculated from

$$I_{Red,Normalized} = \frac{I_{Red}}{NPF_{Red} \cdot ND_{Red}} \qquad (5)$$

where NPF = normalizing power factor, and ND is the ND filter attenuation strength used in the test configuration for the specific measurement. The NPF represents a system an effective throughput for each color band. The NPF is calculated by first multiplying the camera spectral response with the source spectrum. The results are shown for the Photon and Sony cameras in Figure 9. These plots show the system spectral throughput in the absence of the color filters for the Photon and Sony cameras. Integrating each of these functions yields a total system power throughput in the absence of the color filters.
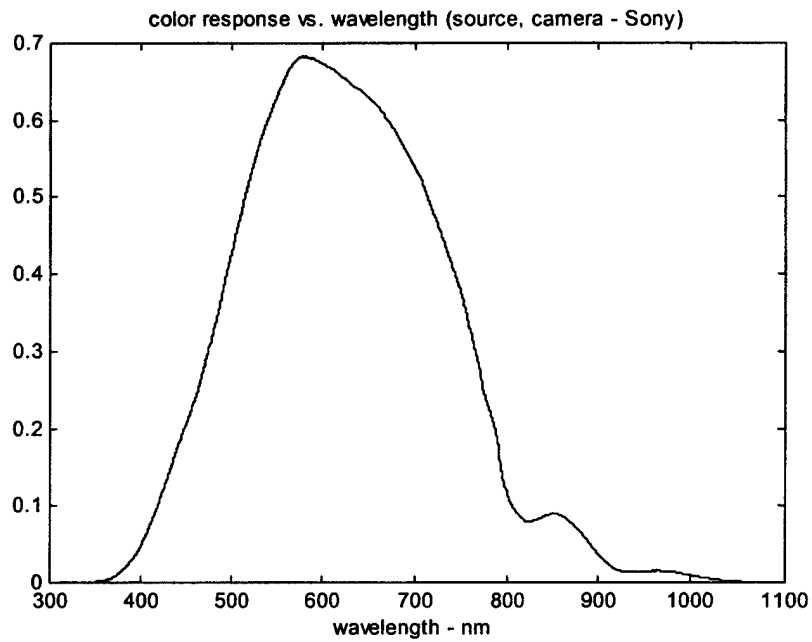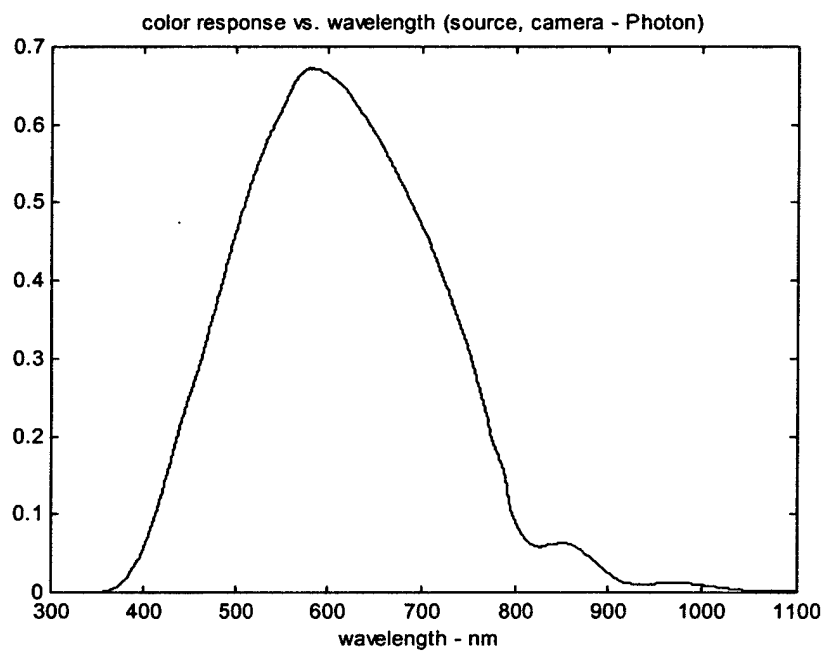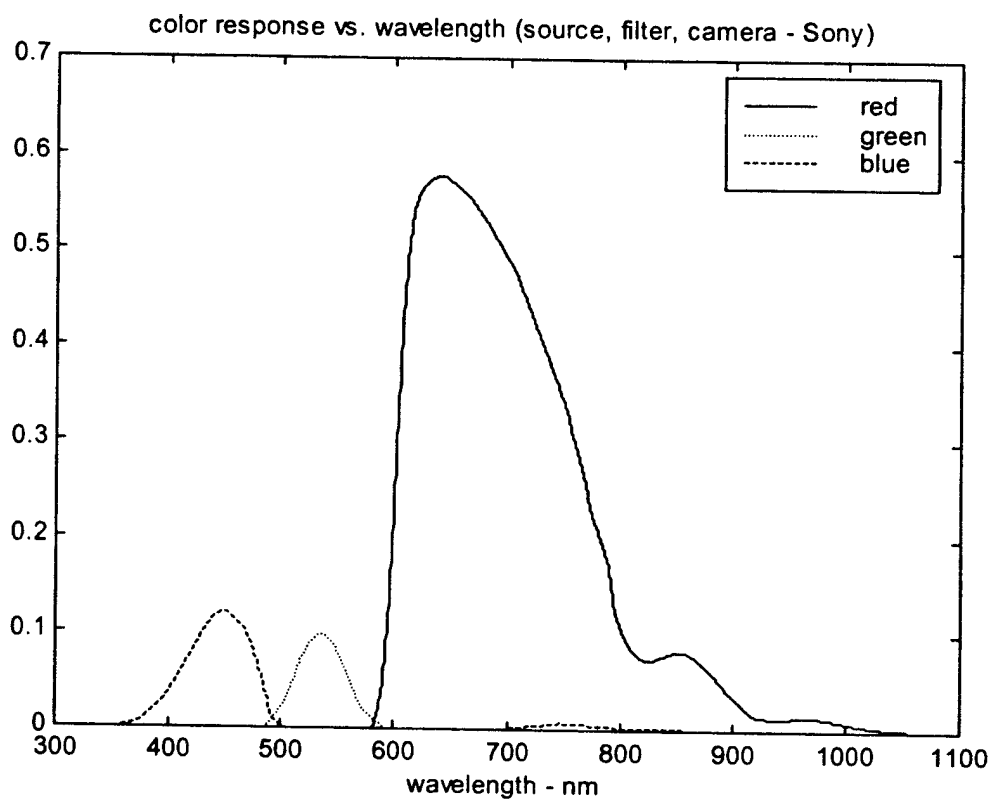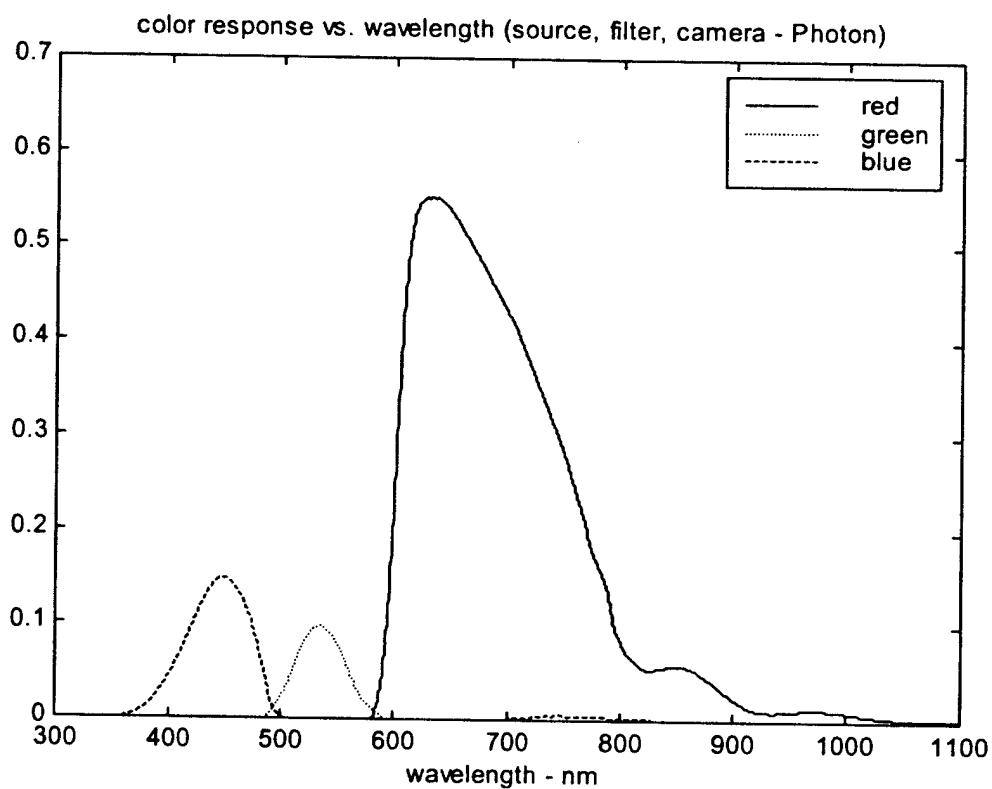
Figure 9. (a) Relative source-camera response with Sony CCD Camera and (b) relative source-camera response with Photon CCD Camera

Next the filter spectral transmission curves shown in Figure 5 are multiplied by the curves shown in Figure 9 to yield the system spectral response in each color-band as shown in Figure 10 for the Sony and Photon cameras.

color response vs. wavelength (source, filter, camera - Sony)

(a)

color response vs. wavelength (source, filter, camera - Photon)

(b)

Figure 10. Relative system response with Sony CCD Camera and (b) relative system response with Photon CCD Camera.

Each color curve is integrated and divided by the normalized system throughput in the absence of the color filters to determine the system throughput in the presence of each color filter. This data is presented in Table 1.

Table 1 Calculated NPF values for the Sony and Photon cameras

	Red NPF	Green NPF	Blue NPF
SONY	0.4660	0.0282	0.0582
Photon	0.5033	0.0268	0.0475

Figure 11 through 18 show profiles of the normalized irradiance patterns (see Equation 5) for the various DCSFs tested. The DCSF naming conventions are shown in Table 2. Note that DCSF1-DCSF3 are 1X, and DCSF4 and DCSF5 are 2X designs. The power in the desired order (color-band) was calculated and this data was fed into Equation 1 and the SNR for each color for the DCSF tested were calculated. This data is presented in Table 3.

Table 2 DCSF naming convention

| DCSF1	DCSF2	DCSF3	DCSF4	DCSF5
1x - Material #1 - No Lens (1cm)	1x - Material #1 - No Lens (1 inch)	1x - Material #2 - No Lens (1 inch)	2x - Material #1 - Lens (1 inch)	2x Tilted - Material #1 - Lens (1 inch) -

Table 3. SNR test results

	DCSF1	DCSF2	DCSF3	DCSF4 at red focus	DCSF4 at green focus	DCSF4 at blue focus	DCSF4 with source data	DCSF5 with no source data	Desired SNR
SNR_R	2.1397	1.2470	8.5026	3.6458	2.9745	3.5259	2.3902	2.9084	5.5882
SNR_G	1.4740	0.4850	8.3200	4.1912	4.3559	4.5428	5.1411	3.3132	5.7895
SNR_B	0.6716	0.6333	0.3139	2.9929	3.0143	2.9926	3.3371	3.4691	5.5882

Note that the NPFs of 0.4660, 0.0282, and 0.0582 were adjusted to 0.3674, 0.0064, and 0.0142 for the red, green, and blue color bands, respectively, when using Material #2. This was due to the 73%, 24%, and 30% transmission values of the red, green, and blue color bands, respectively, for this material.
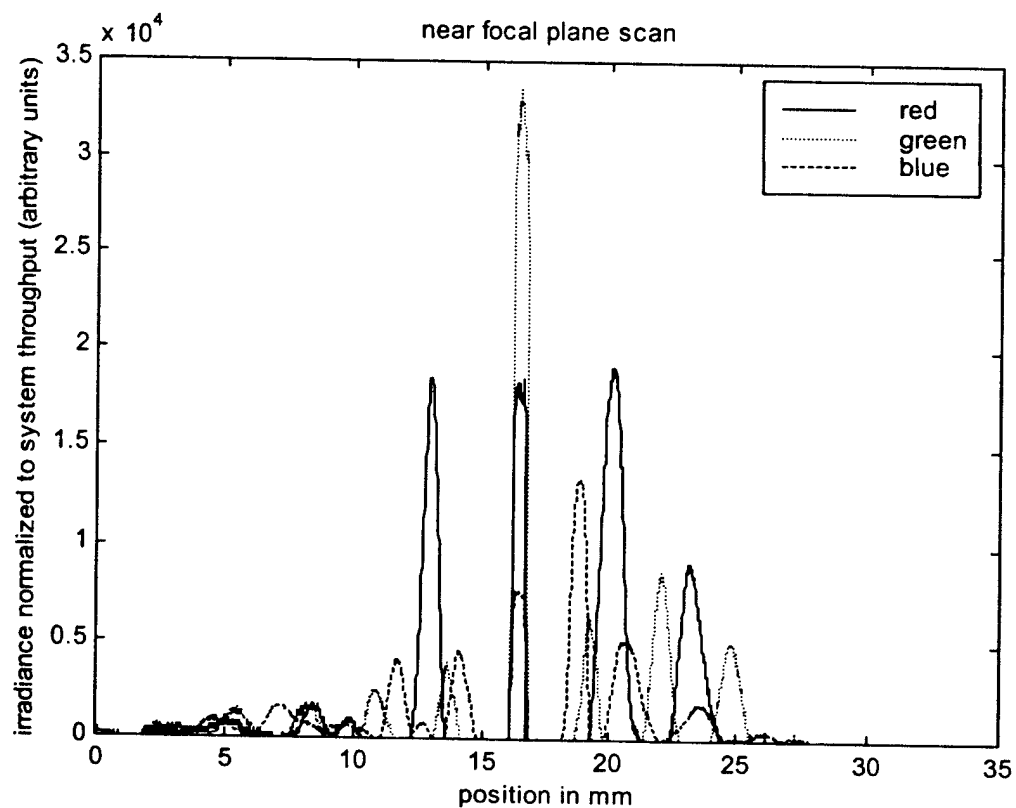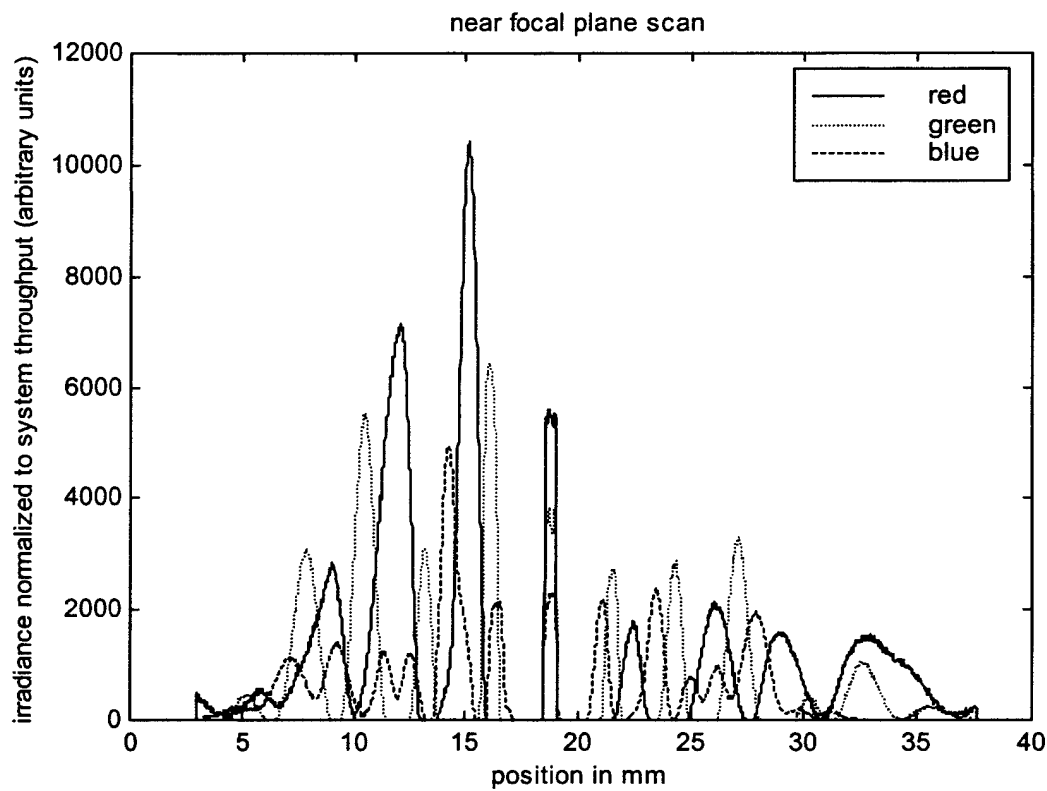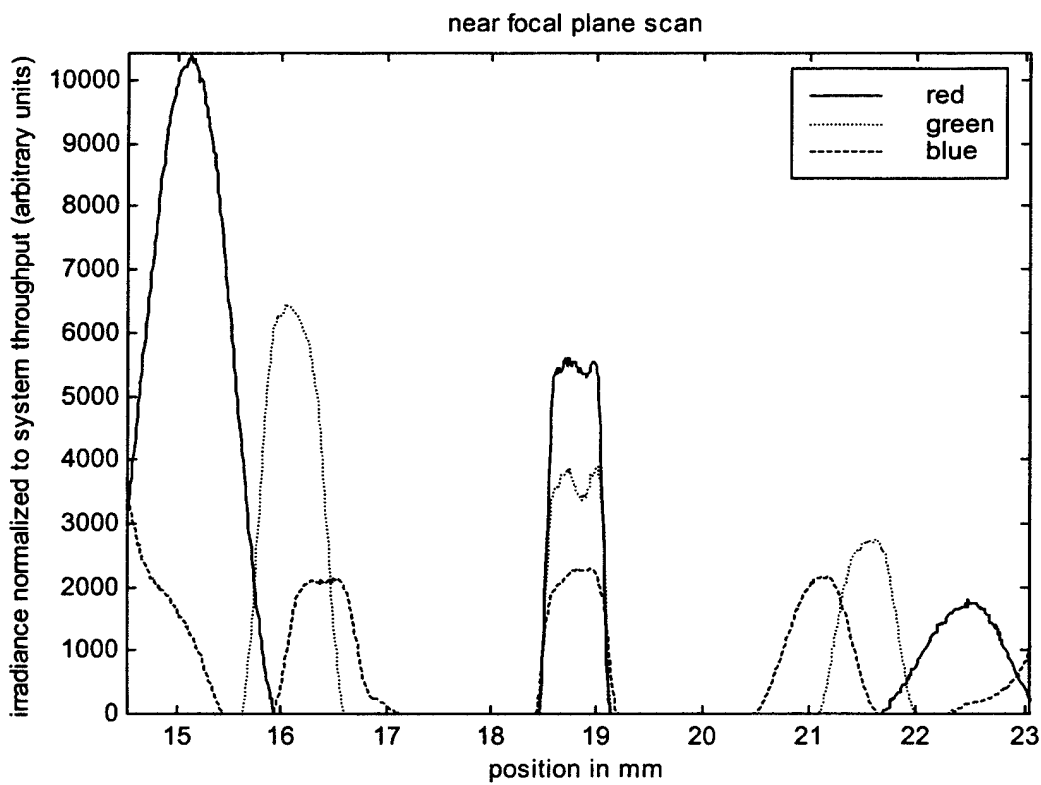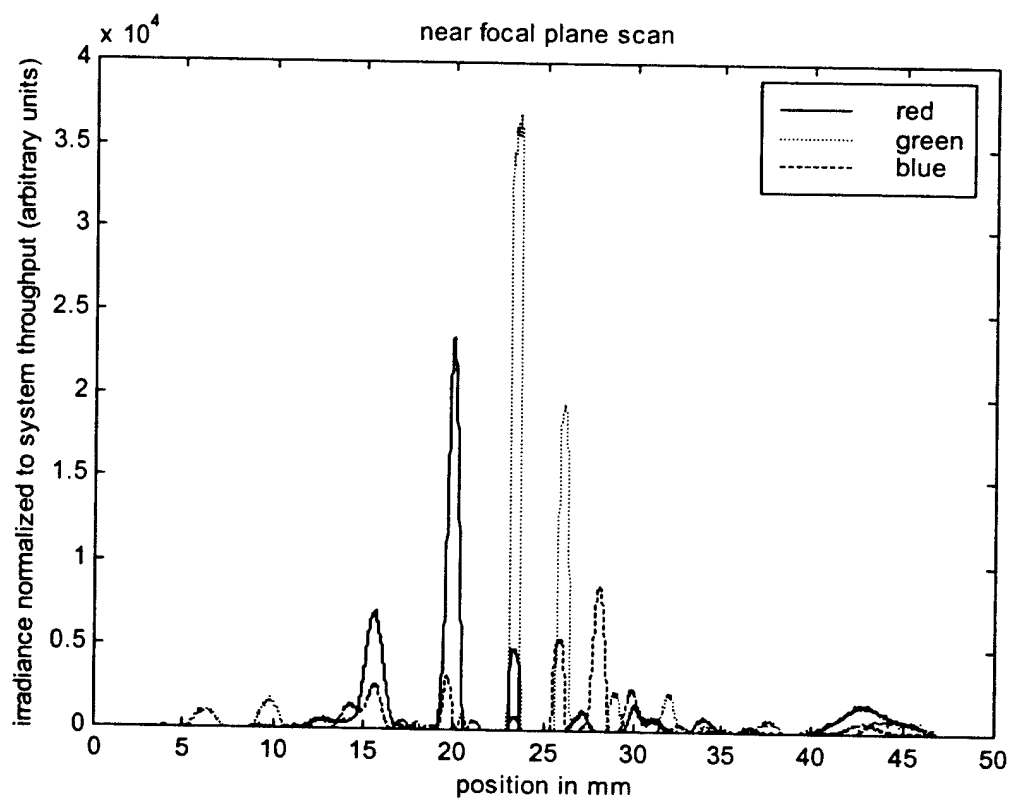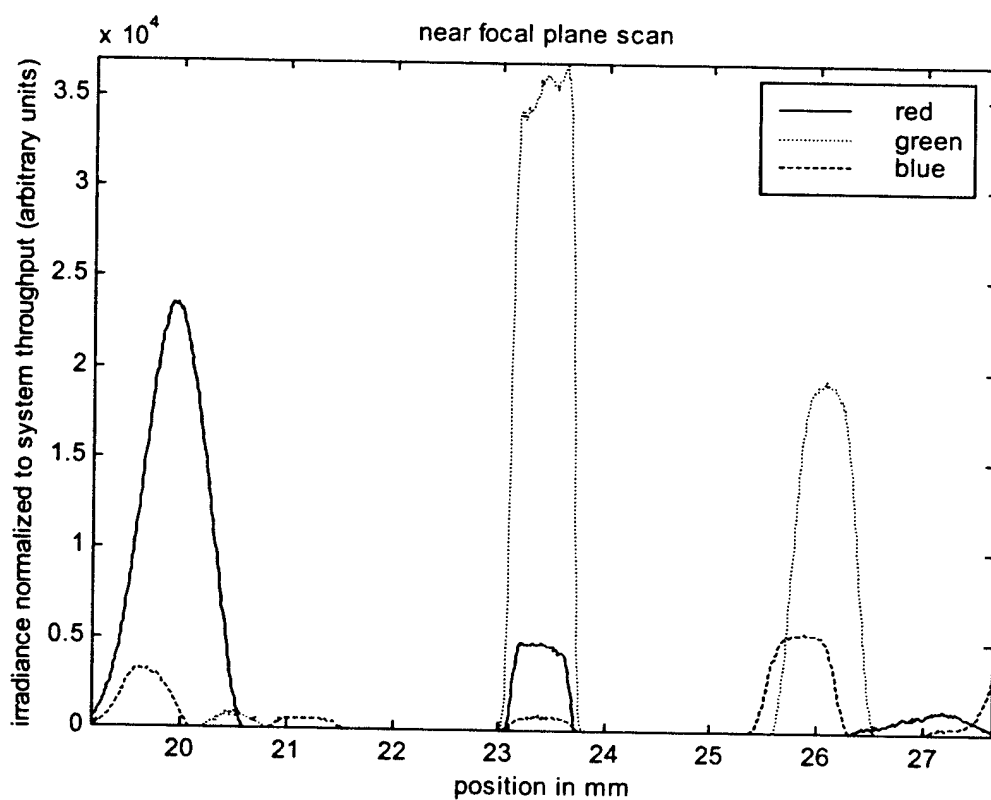
(a)
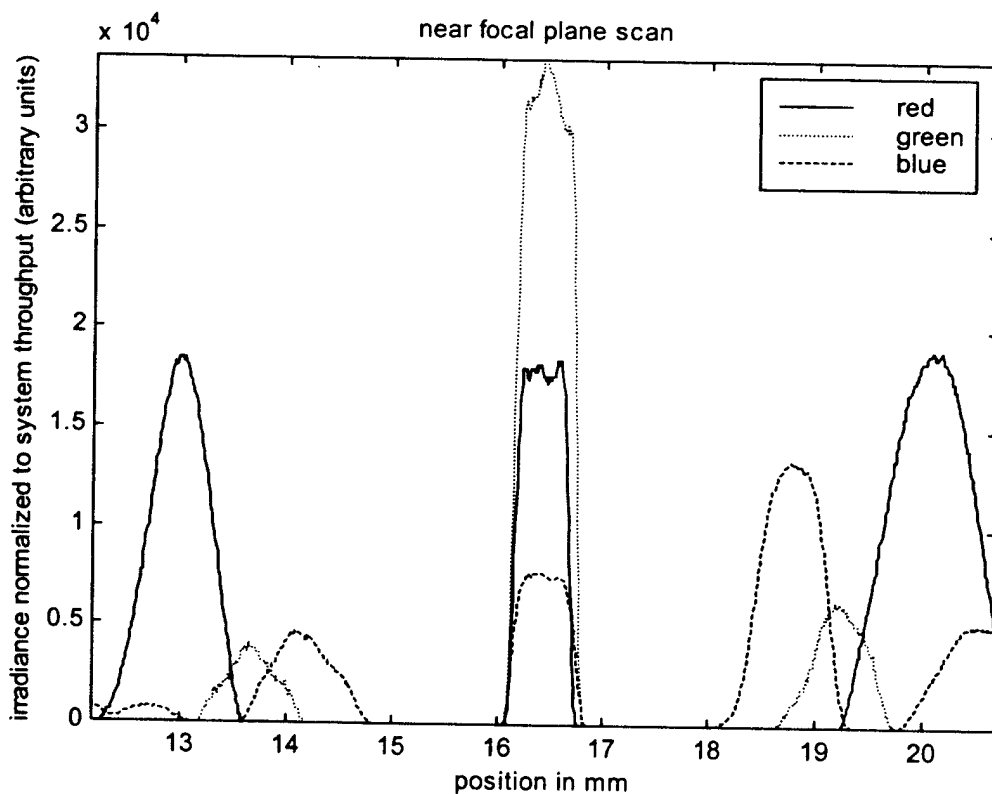
(b)

Figure 11. Profile of normalized irradiance distribution near the focal plane for (a) the entire field of view and (b) for the region containing the -1, 0, and +1 diffraction orders. The data was taken using DCSF1.

Figure 12. Profile of normalized irradiance distribution near the focal plane for (a) the entire field of view and (b) for the region containing the -1, 0, and +1 diffraction orders. The data was taken using DCSF2

(a)

(b)

Figure 13. Profile of normalized irradiance distribution near the focal plane for (a) the entire field of view and (b) for the region containing the -1, 0, and +1 diffraction orders. The data was taken using DCSF3

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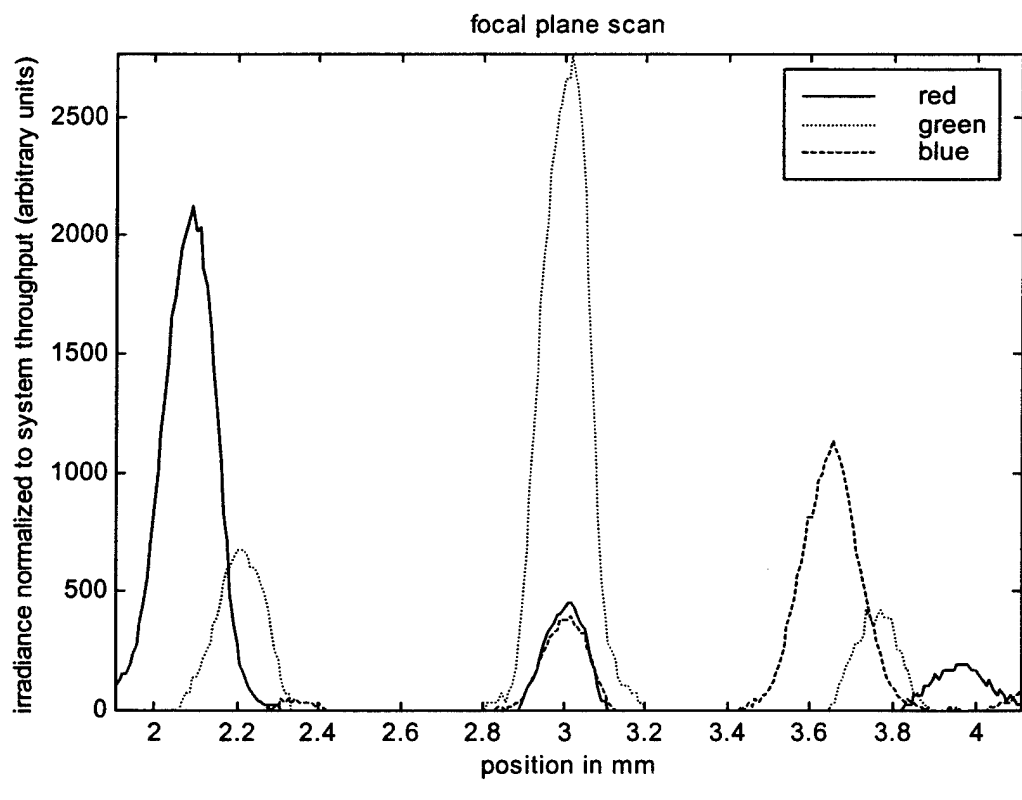**focal plane scan** (a)
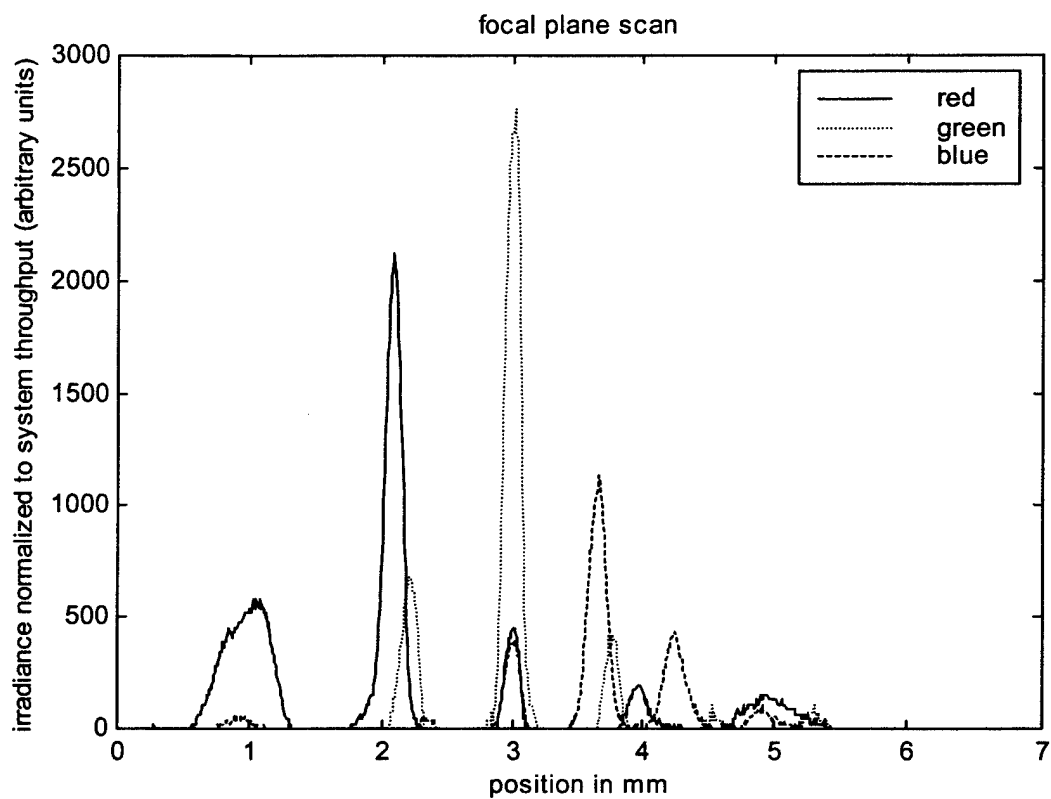
focal plane scan (b)

Figure 14. Profile of normalized irradiance distribution near the focal plane for (a) the entire field of view and (b) for the region containing the -1, 0, and +1 diffraction orders. The data was taken using DCSF4 at the red focus.

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Figure 15. Profile of normalized irradiance distribution near the focal plane for (a) the entire field of view and (b) for the region containing the -1, 0, and +1 diffraction orders. The data was taken using DCSF4 at the green focus
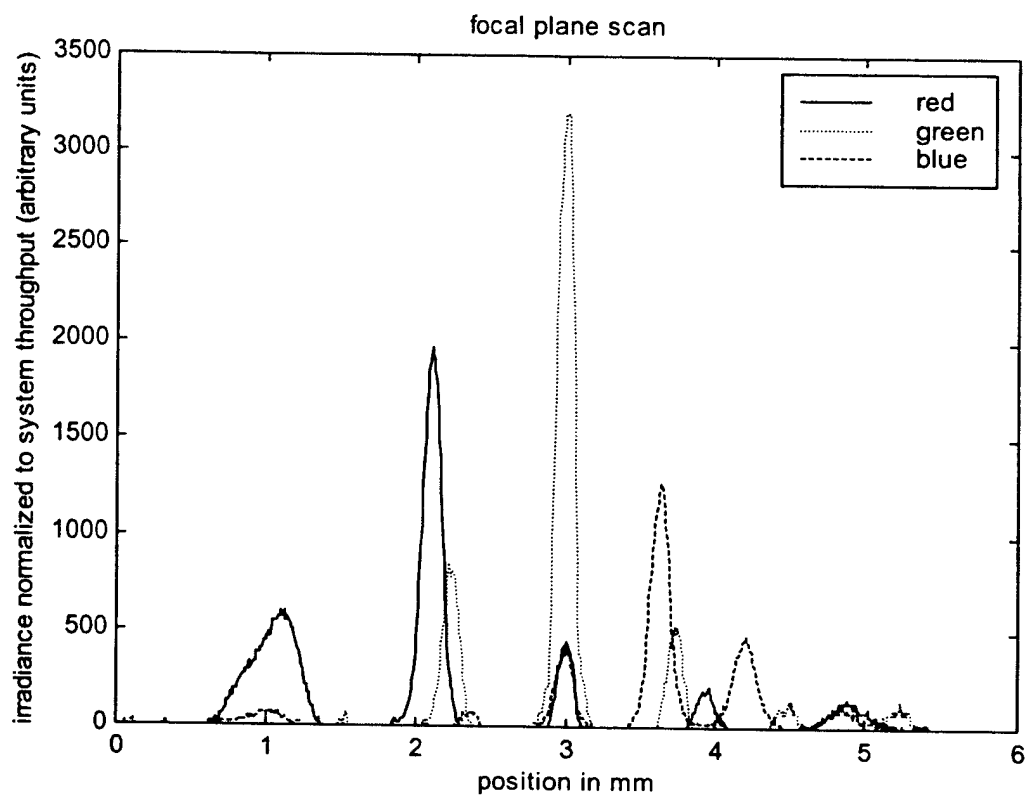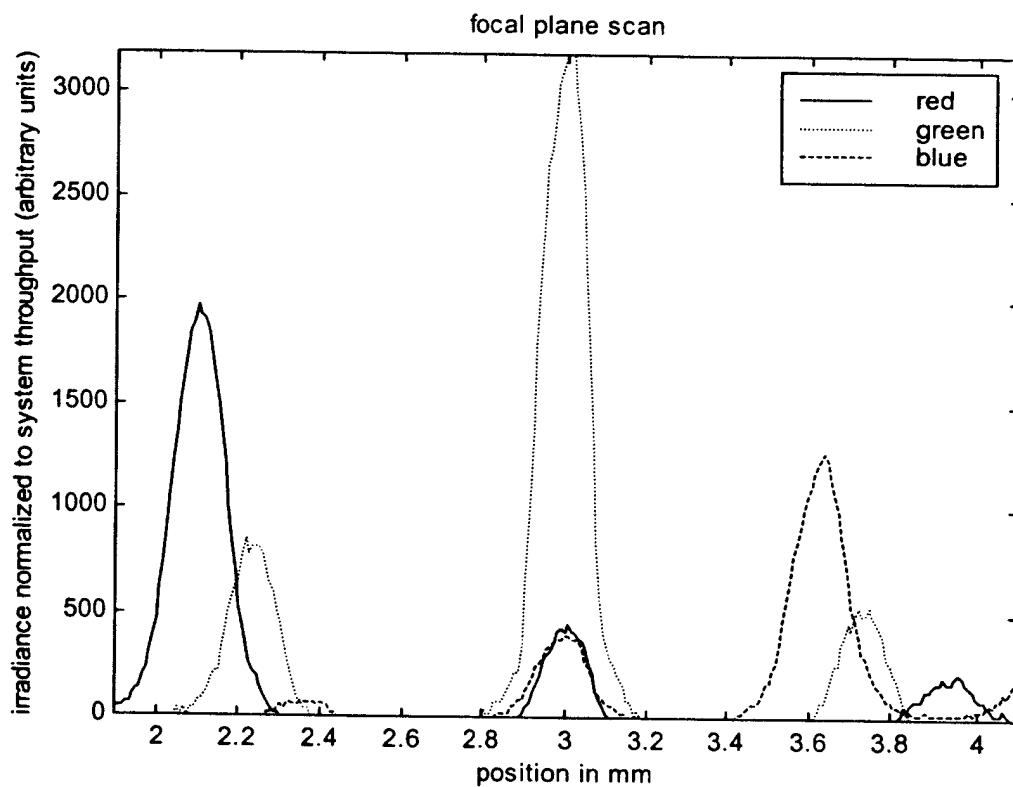
Figure 16. Profile of normalized irradiance distribution near the focal plane for (a) the entire field of view and (b) for the region containing the -1, 0, and +1 diffraction orders. The data was taken using DCSF4 at the blue focus
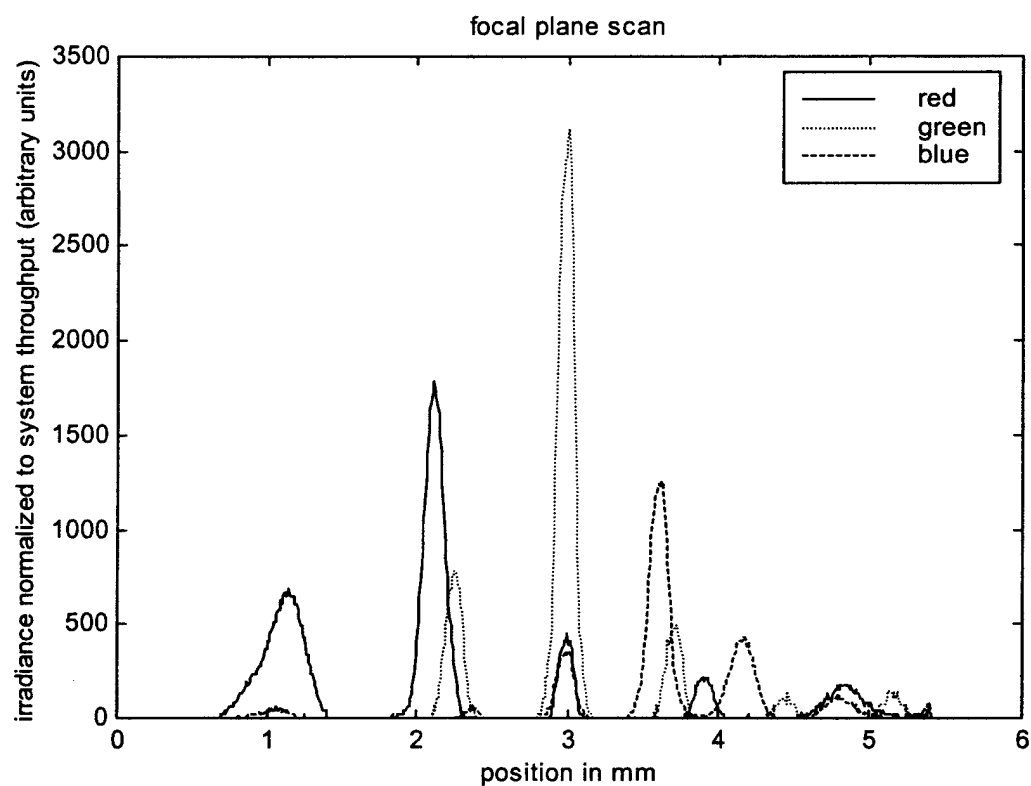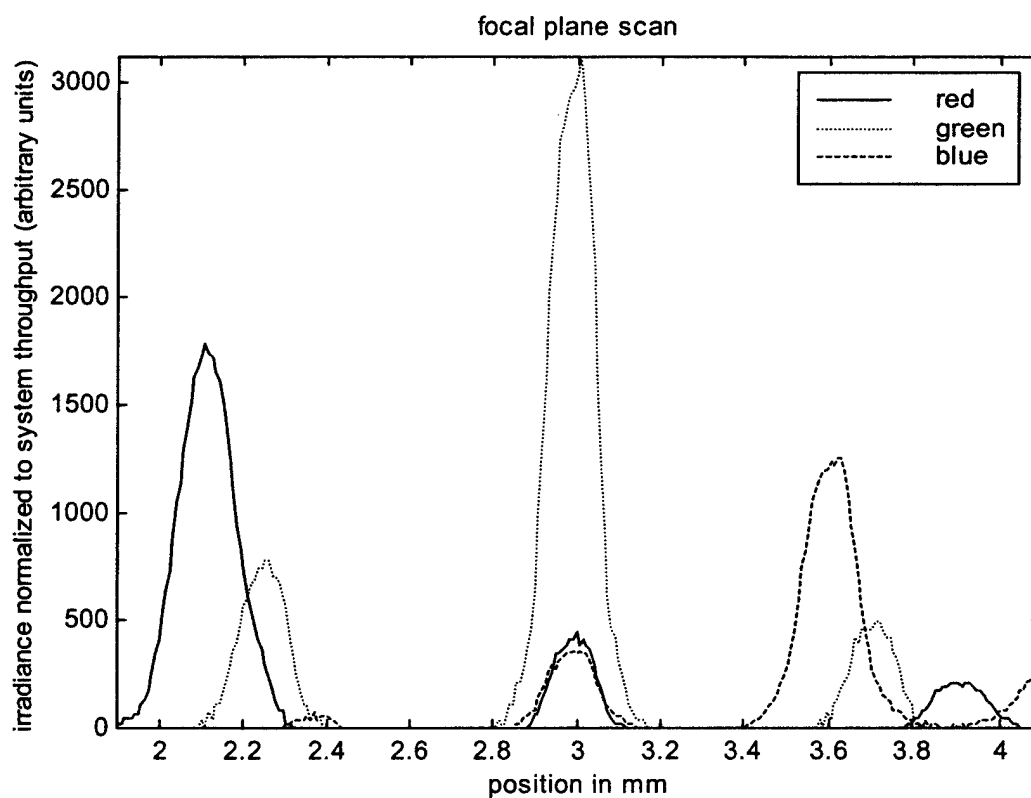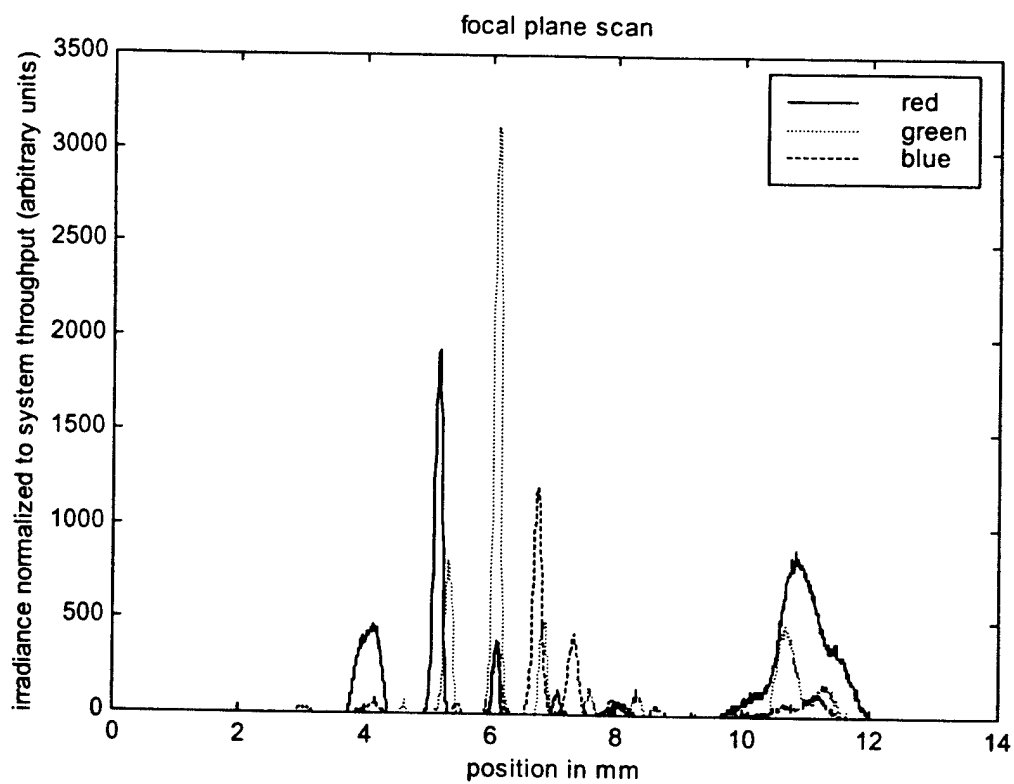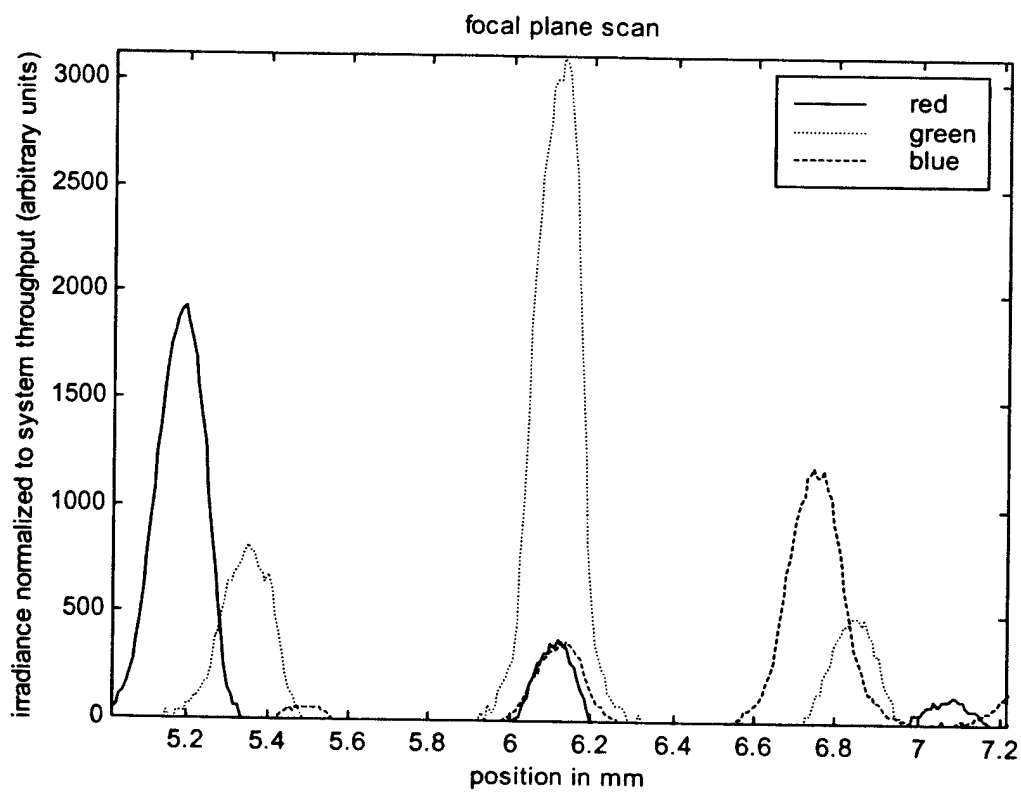
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(a)

(b)

Figure 17. Profile of normalized irradiance distribution near the focal plane for (a) the entire field of view and (b) for the region containing the -1, 0, and +1 diffraction orders. The data was taken using DCSF4 at intermediate foci
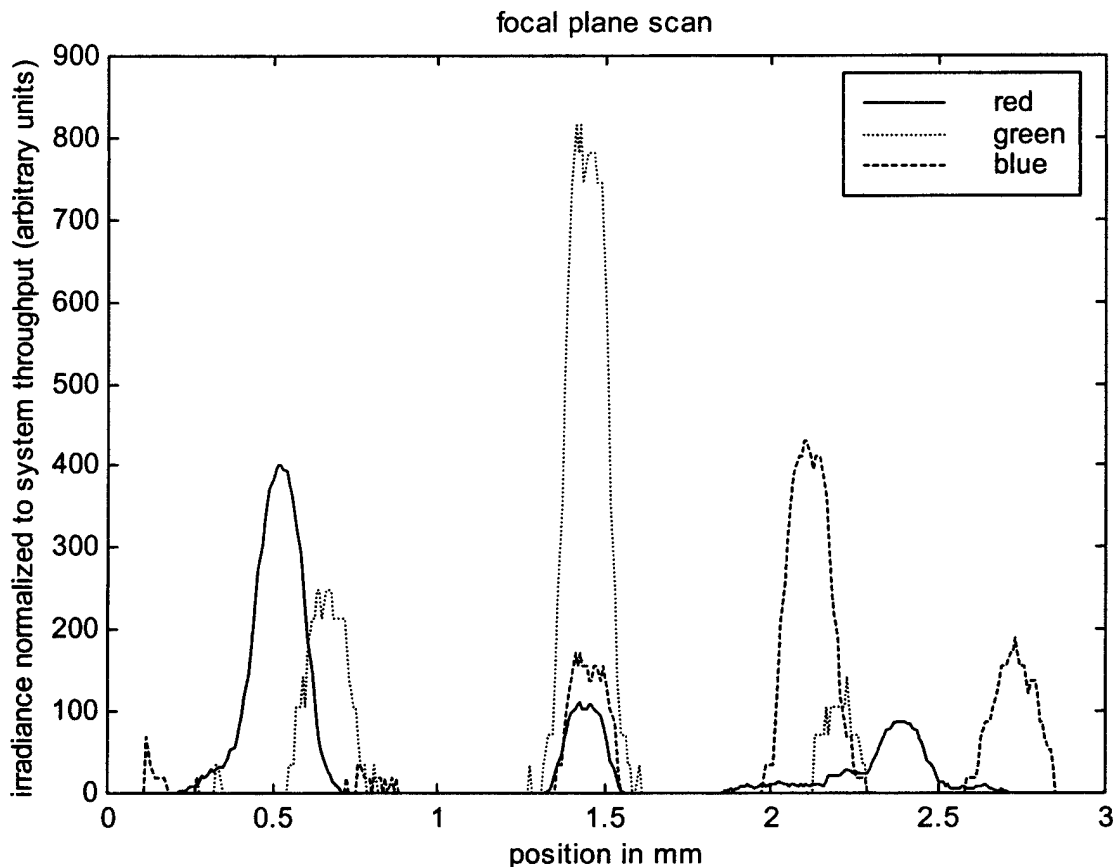
Figure 18. Profile of normalized irradiance distribution near the focal plane for the region containing the -1, 0, and +1 diffraction orders. The data was taken using DCSF5 at intermediate foci.

The SNR results indicate that the 2X DCSF design provides the overall highest SNR for all available color bands through the primary orders. However, examination of the entire focal plane shows that there is loss outside of the -1, 0, and +1 orders for all DCSF designs considered. It was discovered that the 2X design undesirable slopes instead of steep side walls in the etched optic. This accounts for the large amount of light scattered into the -2 order. The 1X DCSF design had possible misalignment errors during the exposure process, which may account for the excess light scattered across the focal plane.

Efficiency was calculated based on the normal power in an undeviated beam through the optic material. In all DCSFs, other than DCSF4, the optic was manufactured on a test substrate that contained areas of unetched optic material. The test configurations were adjusted so that the collimated light was incident on the unetched area of the substrate. Figure 19a shows an undeviated beam captured for DCSF1 using the 1X test configuration. DCSF4 and DCSF5 had already ready been diced from their substrates at the time of test, so this test could not be performed. Instead, a single lens element was apertured, as shown in Figure 19b, and the apertured element was imaged on the CCD. This was used as the undeviated beam irradiance. The aperturing hardware was unavailable at the time DCSF5 was available for test. Therefore, an efficiency measurement, based only on the irradiance detected at the focal plane, was determined

for DCSF5 (as shown in Figure 19c). DCSF5 is designed so that undesired diffraction components are tilted away from the desired sub-pixel aperture.
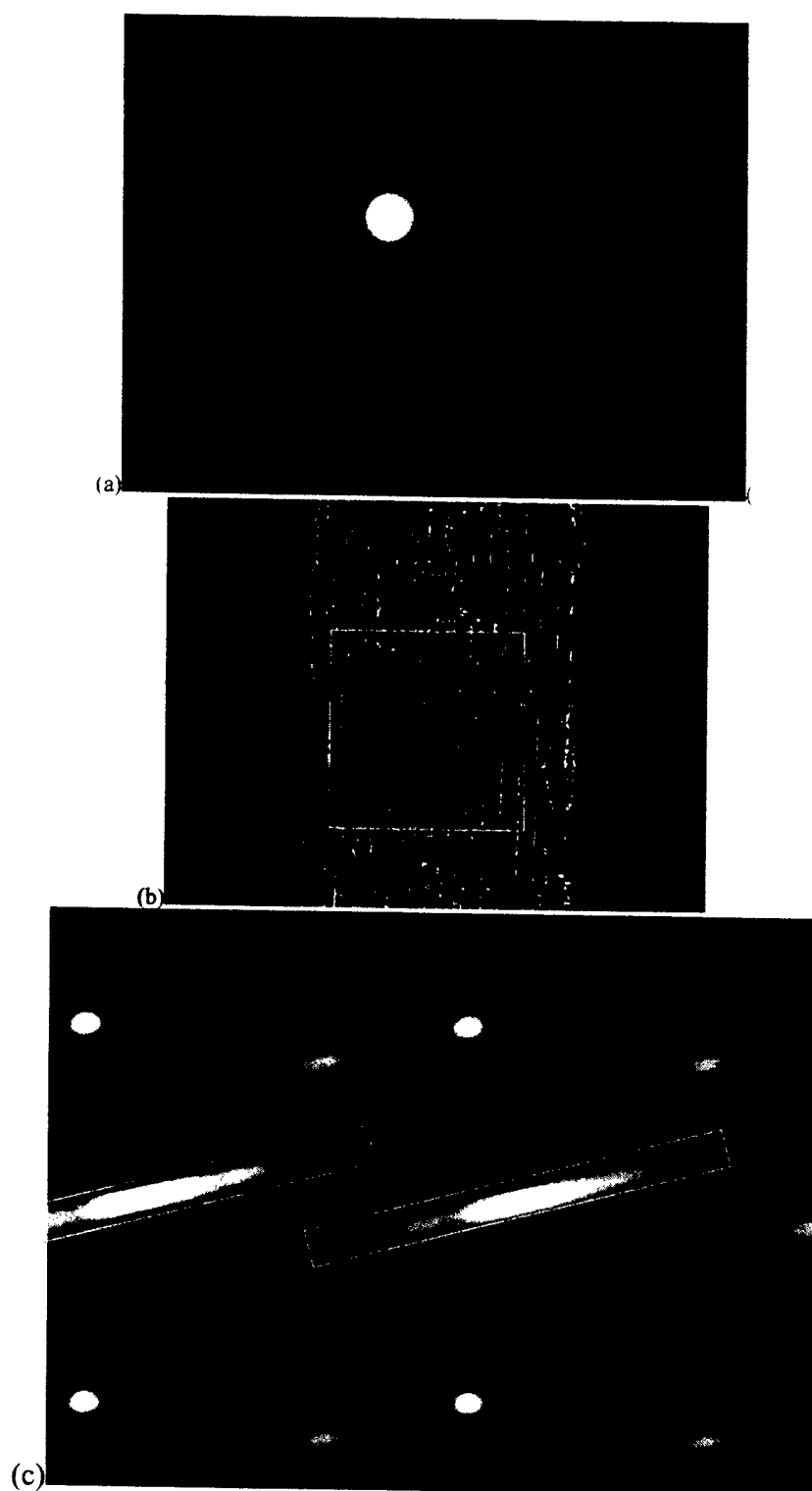

Figure 19 (a) Red undeviated beam obtained for DCSF1, (b) green undeviated beam imaged at DCS4, and (c) red tilted irradiance pattern resulting from DCSF5. Sub-figures (b) and (c) have been contrast enhanced)

The efficiency measurements are shown below in Tables 4 and 5. Table 4 shows the efficiency measurements relative to the captured "undeviated" beam power. Table 5 shows the efficiency measurements relative to the captured diffracted power. The boxes in Figure 19b and 19c are the regions for which the power data was calculated. Note that there is a significant difference in the efficiency measurements for the undeviated and captured diffracted irradiance for the 1X design. This appears to be due to vignetting by the focusing lens because the 1X design is a "fast" pattern - i.e., higher angular spread than the 2X pattern. However, the efficiency ratios in Table 4 and Table 5 for the 1X pattern are approximately equal. Also, in the undeviated beam tests for DCSF4, 2σ was used in the threshold calculation instead of 4σ (see Equation 3). This was due to the fact that the irradiance values in the captured image were not much greater than the noise irradiance values. Note that, in general, although the 2X designs had better SNR in the desired apertures, the efficiency for the red is generally poorer than in the 1X designs. Figures 14a through 17a show that there is a blurring of several higher order red terms that accounts for a significant amount of energy. Overall the 1X designs had poorer blue performance. This may be due to inaccuracies in the normalization calculations. It is also possible that this results from the poorer SNR for the blue in the unthresholded irradiance patterns captured with the CCD. The Sony camera used for the 1X (DCSF1-3) tests had lower SNR than the Photon camera used for the 2X (DCSF4-5). Also, the Photon camera is designed for laser beam measurements where the Sony is simply a conventional imaging array. Therefore, the SNR performance for the source's low blue emittance is probably the biggest contributor to the low blue SNR and Efficiency numbers. It is also possible that the green is slightly over corrected for a similar reason: while the source's blue emittance is quite low, the green filter transmission is even lower.

Table 4 DCSF efficiency test results relative to "undeviated" beam

	DCSF1	DCSF2	DCSF3	DCSF4 at red focus	DCSF4 at green focus	DCSF4 at blue focus	DCSF4 with source data	DCSF5 with no source data
EFF_{Red}	0.1447	0.1031	0.1968	*****	*****	*****	0.0830	*****
EFF_{Green}	0.3210	0.0332	0.1977	*****	*****	*****	0.5486	*****
EFF_{Blue}	0.2879	0.0354	0.0714	*****	*****	*****	0.4876	*****

Note: Efficiencies are expressed as ratios, not percentages

Table 5 DCSF efficiency test results relative to captured irradiance pattern

	DCSF1	DCSF2	DCSF3	DCSF4 at red focus	DCSF4 at green focus	DCSF4 at blue focus	DCSF4 with source data	DCSF5 with no source data
EFF_{Red}	0.2428	0.2117	0.4282	0.4639	0.4966	0.4903	0.2176	0.0727
EFF_{Green}	0.5171	0.0690	0.5126	0.7473	0.7184	0.7285	0.5518	0.3242
EFF_{Blue}	0.3880	0.0724	0.1852	0.5953	0.5728	0.6152	0.5286	0.3928

The Efficiency was calculated for DCSF5 relative only to the captured irradiance pattern because, as mentioned before, the aperturing element was not available for this test. However, the tilted design (as Figure 19c shows) allowed segmentation of the output from each focusing element with very little overlap from any other element. Thus, a significant amount of the desired incident light was captured at the detector. Therefore, these Efficiency numbers are expected to be close to what would be calculated for Table 5. This can be seen in the similarity to the DCSF4 efficiency calculations shown in Table 4. Again, overall efficiency is poorer in the red.

It can be seen from Figure 13a that the SNR and EFF for DCSF3 is low due to peak doubling and the desired peak appearing in the next order. However, this material results in the best overall signal in the desired region (or very near to the desired region) relative to the noise in any other (undesired) order.

As an addendum, the ND filter values used in the measurements are shown in Table 6 and 7.

Table 6. ND filter values used for test results relative to captured irradiance pattern

	DCSF1	DCSF2	DCSF3	DCSF4 at red focus	DCSF4 at green focus	DCSF4 at blue focus	DCSF4 with source data	DCSF5 with no source data
ND_R	2.0000	1.4000	1.6000	1.0000	1.0000	1.0000	1.0000	0.1300
ND_G	0.8000	0.0000	0.0300	0.0000	0.0000	0.0000	0.0000	0.0000
ND_B	0.5000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table 7. ND filter values used for test results relative to "undeviated" beam

	DCSF1	DCSF2	DCSF3	DCSF4 at red focus	DCSF4 at green focus	DCSF4 at blue focus	DCSF4 with source data	DCSF5 with no source data
ND_R	2.6000	2.6000	2.4000	1.0000	1.0000	1.0000	0.0000	0.1300
ND_G	1.1000	1.1000	0.7000	0.0000	0.0000	0.0000	0.0000	0.0000
ND_B	1.2000	1.2000	0.8000	0.0000	0.0000	0.0000	0.0000	0.0000

Another possible source of error in the SNR and EFF calculations may be errors in the "stitching" process. The software used to calculate the pattern matches for stitching could misplace the pattern match depending on noise in the video frame. The noise in the image is largely temporal noise, which varies frame-to-frame. Therefore, the pattern matching surfaces would be slightly different and the software is forced to match patterns based on overall shape. For high signal to noise, the pattern match error is lower, but the calculated error can be larger because the signal is larger. For low signal to noise, the pattern match error can be larger, but the calculated error can be smaller because the signal is smaller. However, these errors can also vary with the size of the region of interest.

Another source of error is in the extrapolation algorithm used to match the source, camera, and filter spectral regimes. This would most prevalent in the blue response for the cameras and the blue response for the wide-band color filter. The original data set stopped at 750nm, where the tail of the curve is rising. The software does a linear extrapolation over regions of a sinusoid. Thus, the tail may approach zero response at higher wavelengths. This would result in a filter response in the red region, which would increase the blue NPF, and decrease the blue SNR.

3. CONCLUSIONS AND PLANS FOR FUTURE RESEARCH

The evidence gathered in this study indicates that in spite of some undesirable results, Material #2 provided the best results for the 1X DCSF designs. It had the best overall signal shape in the desired region, with the least overall power in unwanted orders. The 2X designs had good SNR and EFF, but poor efficiency in the red. There were various possible sources for error but the methods for test and fabrication improvement suggested below should increase the validity of the tests SNR and efficiency of the parts.

Several methods are being explored to increase the validity of these tests. (1) The software-based pattern matching and switching technique will be replaced by a mechanical technique for pattern matching - i.e., high resolution mechanical stages will be used to determine the stopping and starting points for the CCD scans. A mechanical stage with a positioning resolution of a few microns will results in better stitching than the software technique because CCD pixels are approximately 10 microns, and several pixels of error can add significantly to the measurement error. (2) A better optical test architecture will be employed for future tests. This will be a dedicated architecture with better optical alignment. The architecture will have better optical noise screening to lower noise, and as little vignetting as possible. (3) Narrow band interference filters will replace the wide band color filters used in this study. LED sources may replace the wide band source to reduce overlap in the desired regions and to reduce the need to extrapolate spectral performance characteristics of the cameras, filters, and source. (4) The fabrication facility will produce better metrology data on these parts.

Methods are being explored to improve performance of the DCSFs. Material #2 had significant absorption loss at all wavelengths, but predominantly at wavelengths below the red. Methods to improve material characteristics of Material #2 are being investigated. Laboratory metrology capabilities are also being investigated for improvement. Design and fabrication process parameters can then be fine-tuned for better performance. This will result in better performing 1X and 2X Material #1 DCSFs as well as Material #2 DCSFs.

ACKNOWLEDGEMENTS

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